The FLUKA Code:
Design, Physics and Applications

www.fluka.org

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Developed and maintained under an INFN-CERN agreement

More than 4000 users all over the world

Two beginner courses per year, recently an advanced one

The FLUKA International Collaboration

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Applications

- A general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications:
  - proton and electron accelerator shielding
  - target design
  - dosimetry and radiation protection
  - neutronics
  - calorimetry, tracking and detector simulation etc.
  - activation
  - detector design
  - Accelerator Driven Systems (e.g., Energy Amplifier)
  - cosmic ray research
  - space radiation (space related studies partially funded by NASA)
  - neutrino physics
  - hadron therapy

etc.

Particle Interactions and Transport

- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions up to 10000 TeV
  - Nucleus-nucleus interactions up to 10000 TeV/n
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - Charged particle transport and energy loss
  - Transport in magnetic fields
  - Neutron multi-group transport and interactions 0-20 MeV
  - Neutrino interactions up to 100 TeV

Unique features

- Combinatorial (boolean), Voxel and Lattice (repetitive) geometries
- Accurate handling of MCS step near boundaries
- Double capability to run either fully analogue and/or biased calculations
- On-line evolution of induced radioactivity and dose
- User-friendly GUI interface Flair (FLUKA Advanced InteRface):
  - for input preparation
  - geometry editing and debugging
  - analysis and presentation of results

Code Design I

- **Sound and modern physics**
  - Based, as far as possible, on original and well-tested microscopic models
  - All steps (Glauber-Gribov cascade, (G)INC [1], preequilibrium, evaporation / fragmentation / fission) self-consistent and with solid physical bases
  - Optimized by comparing with experimental data at single interaction level: **"theory driven, benchmarked with data"**
  - No tuning on "integral" data such as calorimeter resolution, thick target yields, etc.

[1] Generalized IntraNuclear Cascade

Code Design II

- Final predictions obtained with minimal free parameters fixed for all energies, targets and projectiles

→ **FLUKA is NOT a toolkit! Its physical models are fully integrated**

- Results in complex cases, as well as properties and scaling laws, arise naturally from the underlying physical models.

→ **Good environment for "exotic" extensions (ν, nucleon decay…)**

- Basic conservation laws fulfilled "a priori". Energy conserved within 10^{-10}

- Correlations preserved fully within interactions and among shower components

→ **Predictivity where no experimental data are directly available**

Code Design III

- **Self-consistency**
  - Full cross-talk between all components: hadronic, electromagnetic, neutrons, muons, heavy ions
  - Effort to achieve the same level of accuracy:
    - for each component
    - for all energies

- **Other features**
  - Systematic use of relativistic kinematics
  - Tabulated total cross sections & other integral nuclear and atomic data
  - Differential cross sections: not explicitly tabulated, but reaction channels and energies sampled by physical models (event generators) (except for neutrons with $E < 20$ MeV).
  - No mix and match: if a good model is available, use the model

→ We want to preserve correlations as much as possible!

Code Design IV

- **No programming required**
  - All scoring, cutoff setting, biasing, etc. are defined by the user without any need to write code. Writing user routines is encouraged only in very special, complex cases
  - This has allowed to implement very optimized scoring algorithms, much more accurate than what a user could write without a special effort
  - Easy to use. But difficulty to convince users accustomed to other codes...
  - QA guaranteed more easily: users cannot experiment (not a toolkit!), programming is discouraged and input file is a good documentation

The FLUKA hadronic models

Hadron-Nucleon

Elastic, exchange	P<3-5 GeV/c	low En. π, K	High Energy
Phase shifts, data, eikonal	Resonance prod. and decay	Special	DPM hadronization

Hadron-Nucleus

P<4-5 GeV/c	High Energy
PEANUT(1): Sophisticated GINC(2)	Glauber-Gribov Multiple interactions
preequilibrium Coalescence	Coarser GINC(2) Coalescence

Nucleus-Nucleus

E > 5 GeV/u :
DPMJET-III
0.1< E < 5 GeV/u:
(modified) rQMD-2.4(3)
E< 0.1 GeV/u:
BME(4)

Evaporation/Fission/Fermi break-up
γ deexcitation

(1) PreEquilibrium Approach to NUclear Thermalization

(2) Generalized IntraNuclear Cascade

(3) relativistic Quantum Molecular Dynamics

Nuclear interactions in PEANUT:

Target nucleus description (density, Fermi motion, etc)

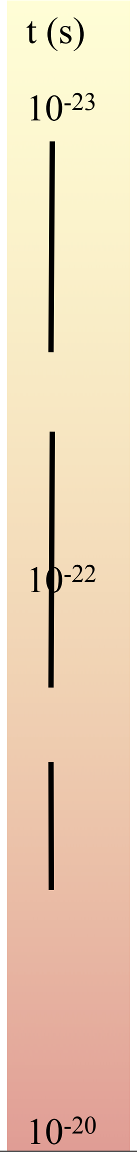
Glauber-Gribov cascade with formation zone

Generalized IntraNuclear cascade

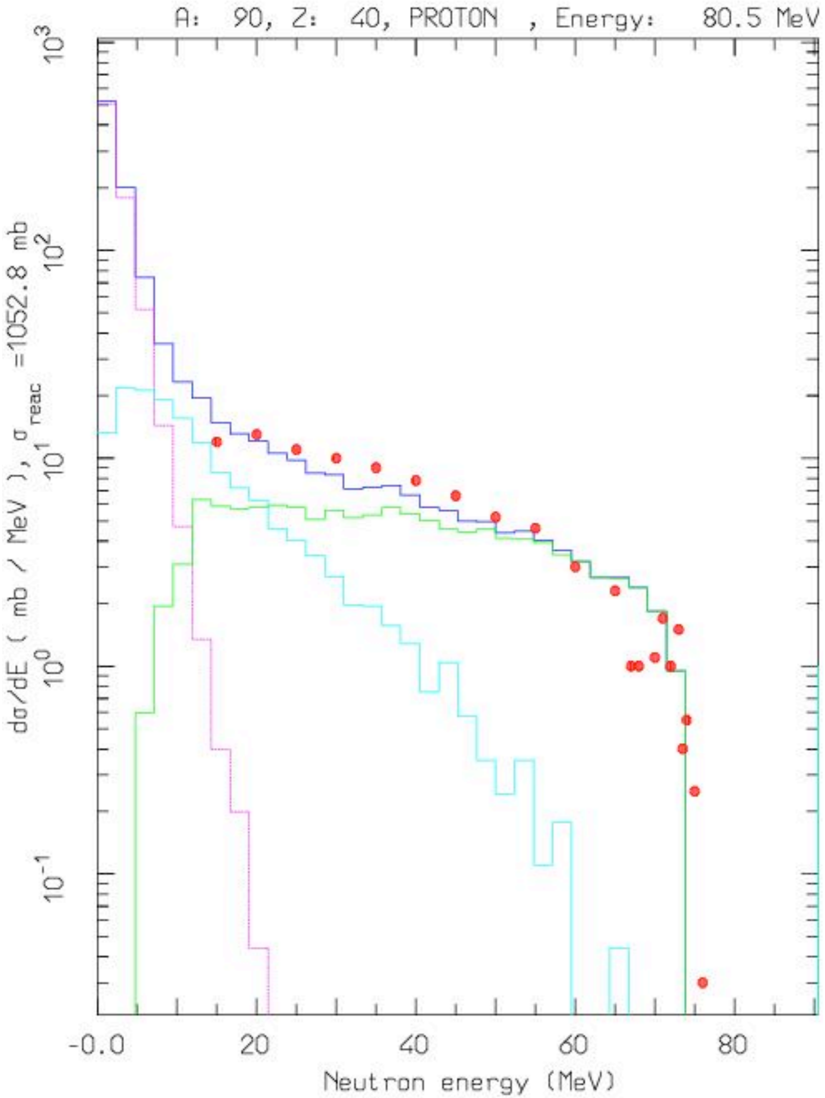
Preequilibrium stage with current exciton configuration and excitation energy (starts when all non-nucleons have been emitted/decayed & all nucleons are below 30-100 MeV)

Evaporation/Fragmentation/Fission

γ deexcitation



Thin target example



Angle-integrated ^{90}Zr(p,xn) at 80.5 MeV

The various lines show the total, INC, preequilibrium and evaporation contributions

Experimental data from
M. Trabandt et al., Phys. Rev. C39, 452 (1989)

(Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear well according to the Fermi gas model
- Interaction probability

  σ_{free} + Fermi motion × $\rho(r)$ + exceptions (ex. π)
- Glauber cascade at higher energies
- Classical trajectories in nuclear mean potential (resonant for π)
- Curvature from nuclear potential → refraction and reflection
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon CMS → Lorentz boosts
- Multibody absorption for π, μ^-, K^-
- Quantum effects (Pauli, formation zone, correlations…)
- Exact conservation of energy, momenta (including nuclear recoil) and all additive quantum numbers,

hA at high energies: Glauber-Gribov cascade with formation zone

- Glauber cascade
  - Quantum mechanical method to compute Elastic, Quasi-elastic and Absorption hA cross sections from Free hadron-nucleon scattering + nuclear ground state
  - Multiple Collisions: expansion of the scattering amplitude
- Glauber-Gribov
  - Field theory formulation of Glauber model
  - Multiple collisions ⇔ Feynman diagrams
  - High energies: exchange of one or more Pomerons with one or more target nucleons (a closed string exchange)

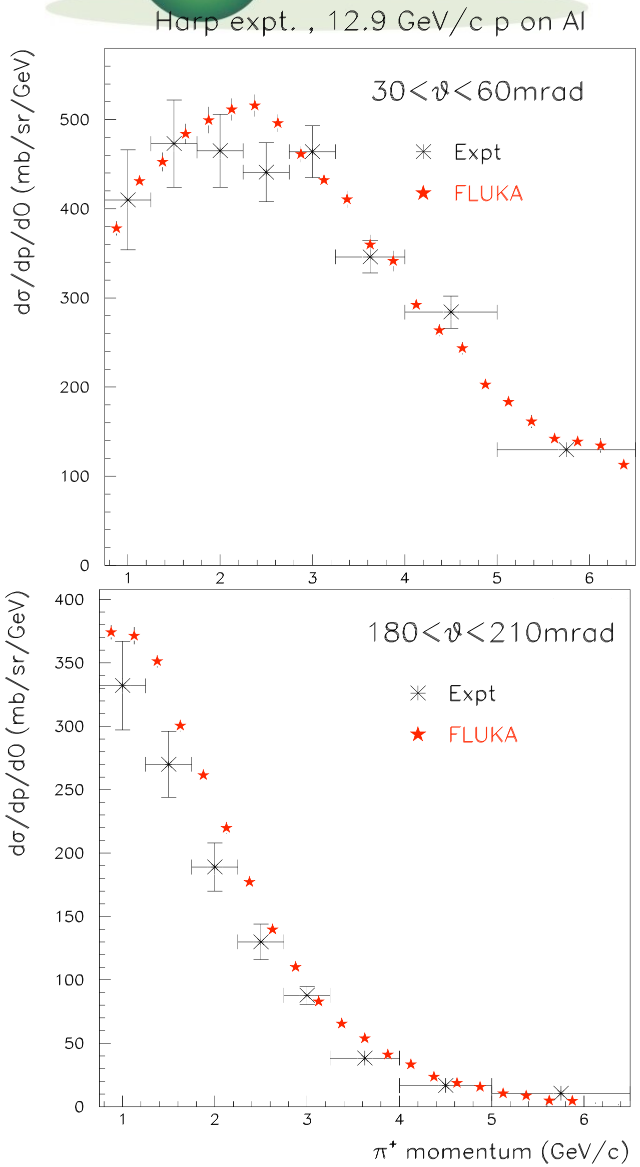
  In the Dual Parton Model language: (neglecting higher order diagrams):

  Interaction with **n** target nucleons ⇒ **2n** chains

  Two chains from projectile valence quarks + valence quarks of one target nucleon ⇒ valence-valence chains

  2(n-1) chains from sea quarks of the projectile + valence quarks of target nucleons ⇒ 2(n-1) sea-valence chains
- Formation zone (= materialization time)

Nonelastic hA interactions

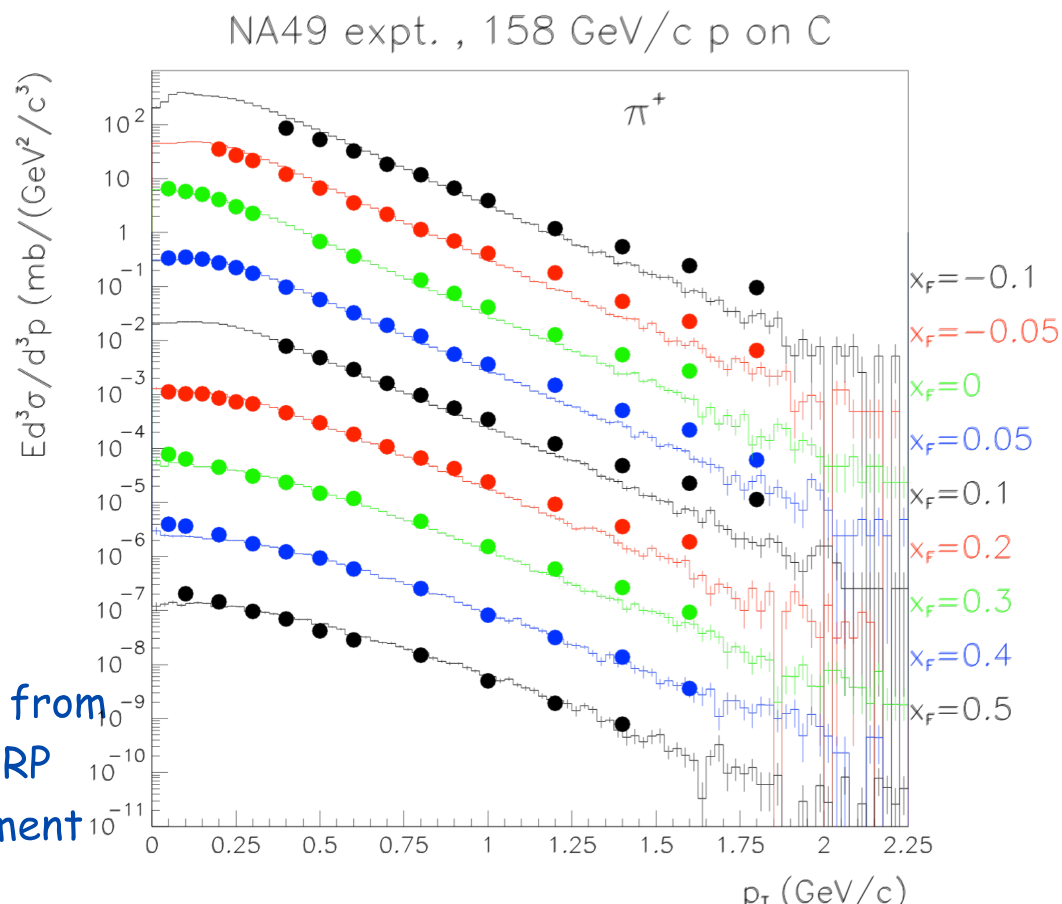


Recent results from the HARP experiment

12.9 GeV/c p on Al

π^+ production

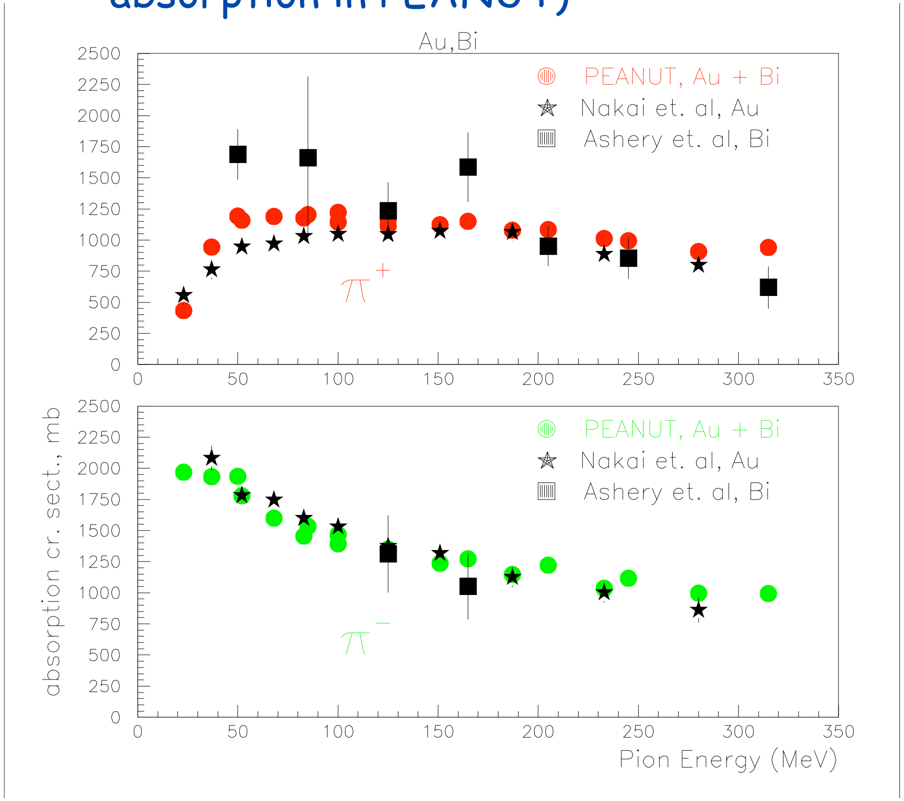
at different angles



Double differential π+ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

Pion absorption

Pion absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)

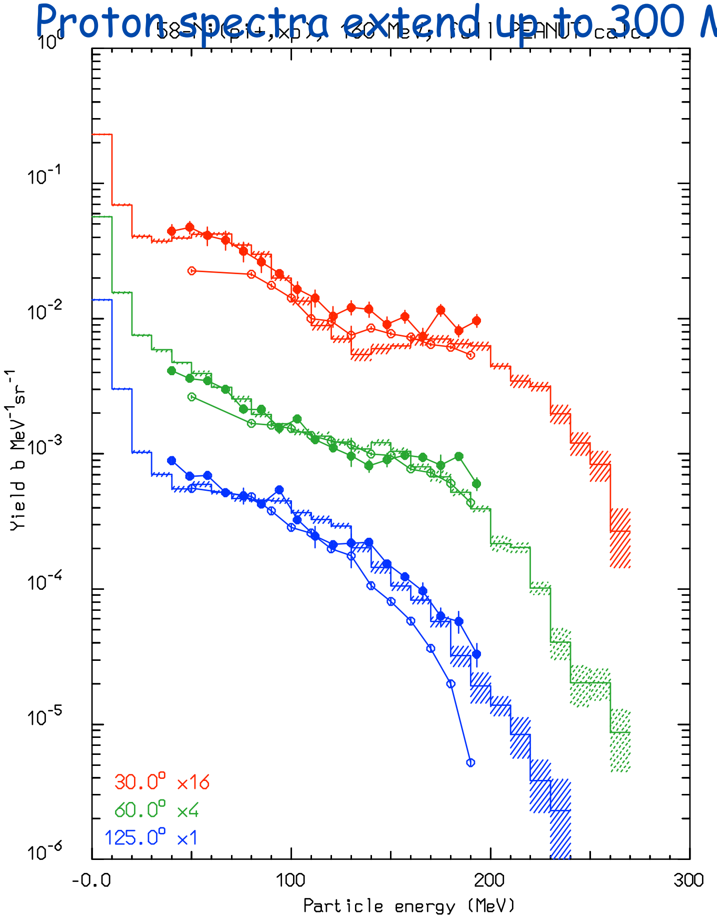


Emitted proton spectra at different angles , 160 MeV π^+ on ^{58}Ni

Phys. Rev. C41,2215 (1990)

Phys. Rev. C24,211 (1981)

Proton spectra extend up to 300 MeV



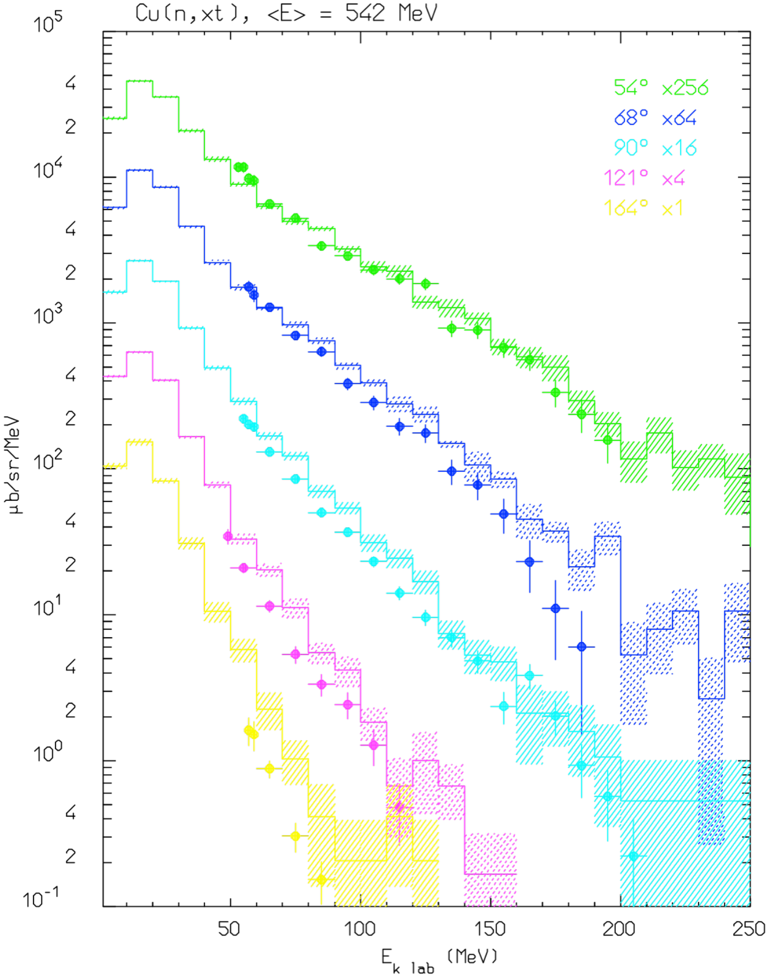
Equilibrium particle emission

- Evaporation: Weisskopf-Ewing approach
  - ~600 possible emitted particles/states (A<25) with an extended evaporation/fragmentation formalism
  - Full level density formula with level density parameter A,Z and excitation dependent
  - Emission energies from the width expression with no. approx.
- Fission: past: improved version of the Atchison algorithm, now:
  - Γ_{fis} based of first principles, full competition with evaporation
  - Improved mass and charge widths
  - Myers-Swiatecki fission barriers. Level density enhancement at saddle point
- Fermi Break-up for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- γ de-excitation: statistical + rotational + tabulated levels

Coalescence

High energy light fragments are emitted through the coalescence mechanism: "put together" emitted nucleons that are near in phase space.

Example : double differential ^3H production from 542 MeV neutrons on Copper



Warning: coalescence is OFF by default

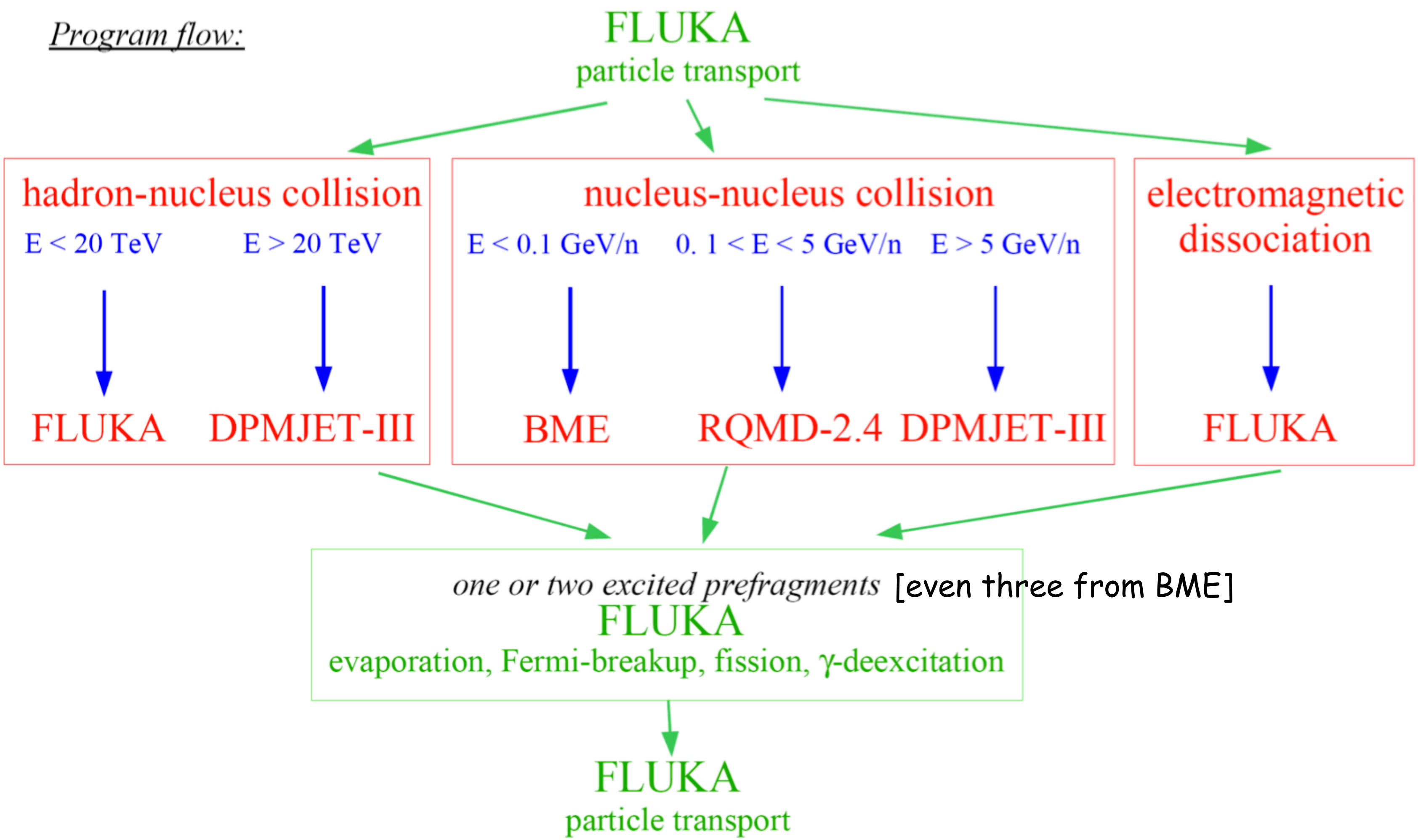
Can be important, ex. for residual nuclei.

Heavy ion interaction models

- DPMJET-III for energies ≥ 5 GeV/n
  - DPMJET (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from 5-10 GeV/n up to the highest Cosmic Ray energies (10^{18}-10^{20} eV)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator
- Extensively modified and improved version of rQMD-2.4 for 0.1 < E < 5 GeV/n
  - rQMD-2.4 (H. Sorge et al.) Cascade-Relativistic QMD model
  - Energy range: from 0.1 GeV/n up to several hundred GeV/n
- BME (Boltzmann Master Equation) for E < 100 MeV/n
  - BME (Gadioli et al.)
  - Energy range: up to 0.1 GeV/n
- Standard FLUKA evaporation/fission/fragmentation used in both Target/Projectile final deexcitation
- Electromagnetic dissociation (Weizsäcker-Williams + photonuclear reactions)

Heavy ion interaction models in FLUKA

Program flow:



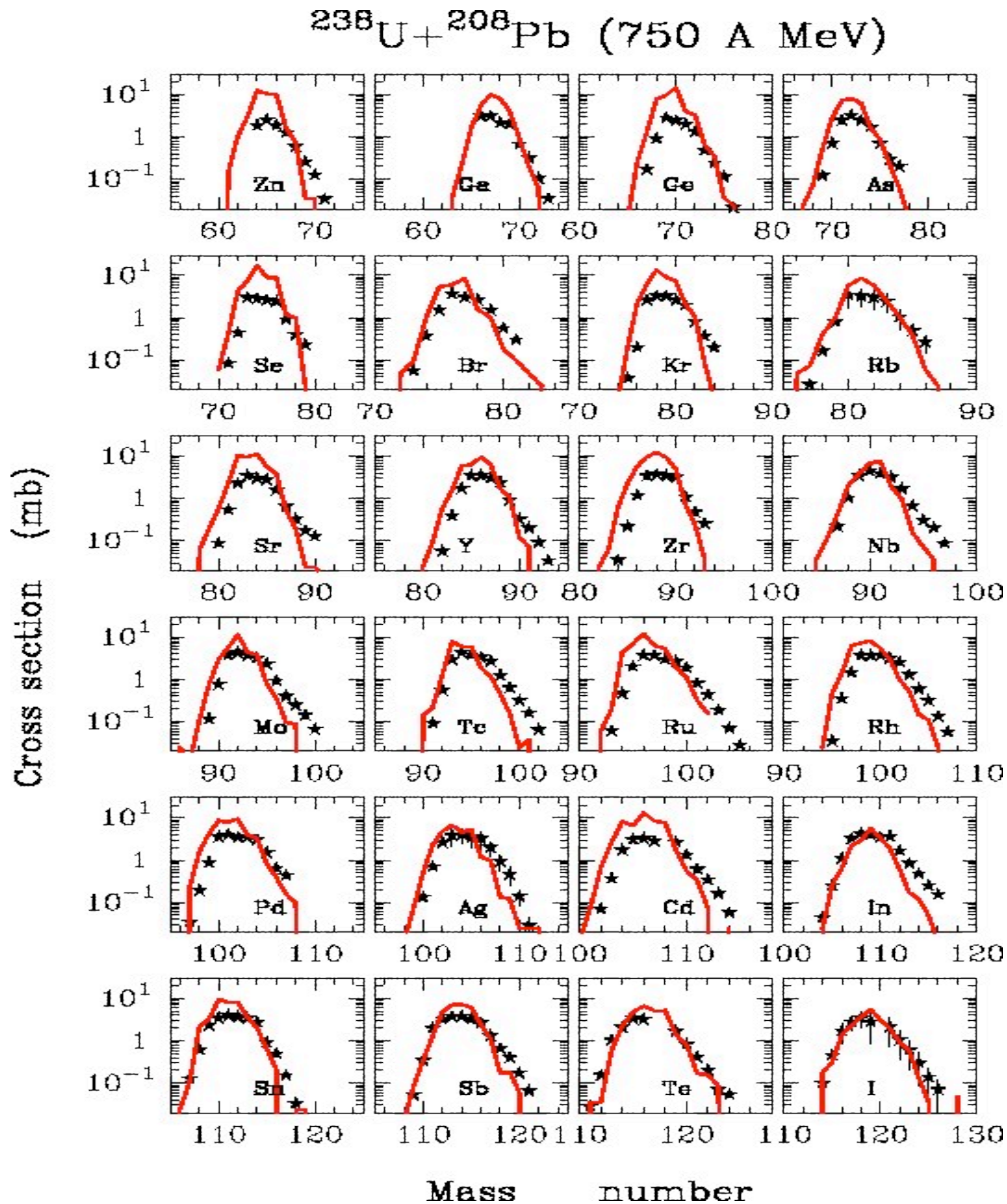
Nucleus-nucleus fragmentation results

Fragment charge cross section for 750 MeV/n U ions on Pb.

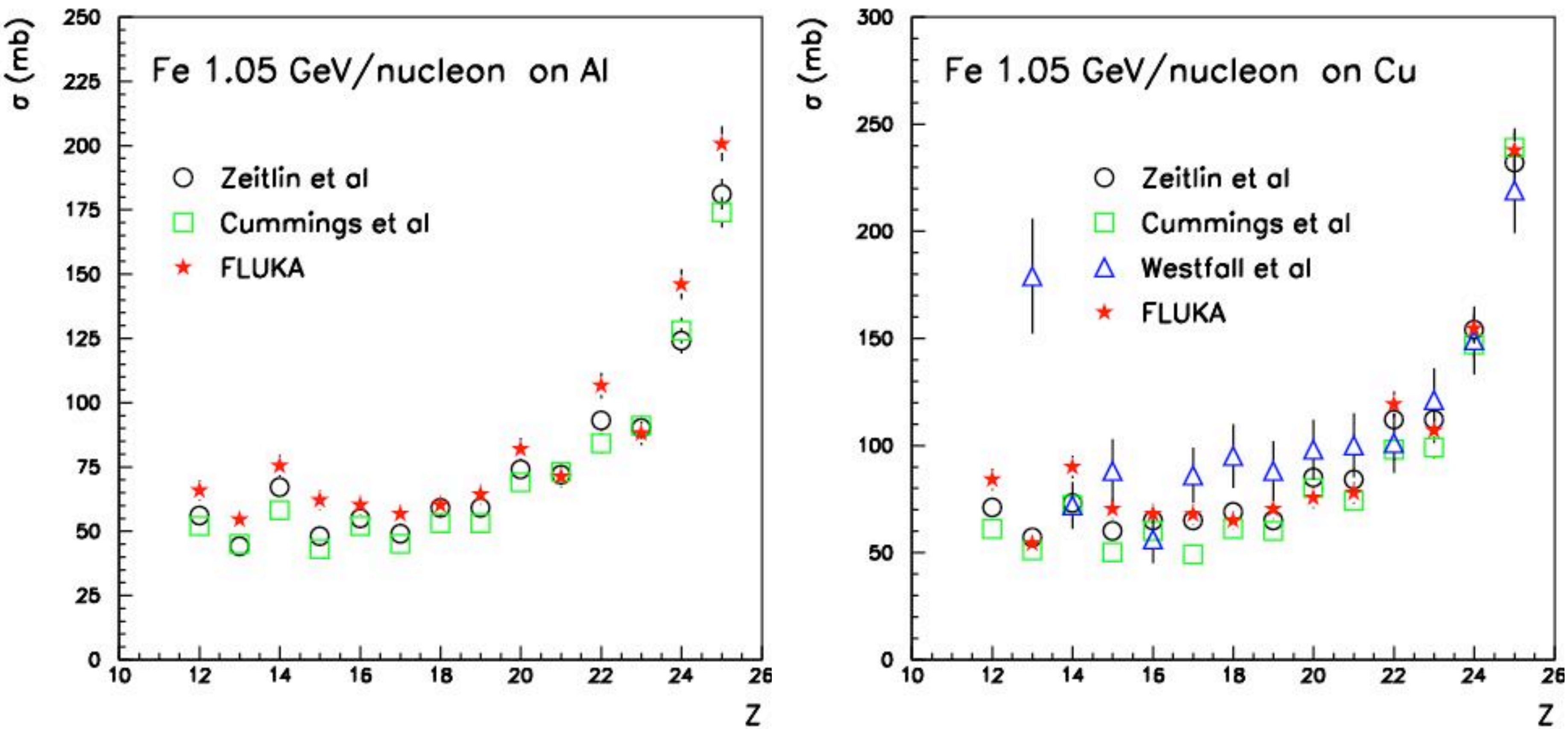
Data (stars) from

J. Benlliure, P. Ambruster et al., Eur. Phys. J. A2, 193-198 (1988).

Fission products have been excluded like in the experimental analysis



FLUKA with modified RQMD-2.4

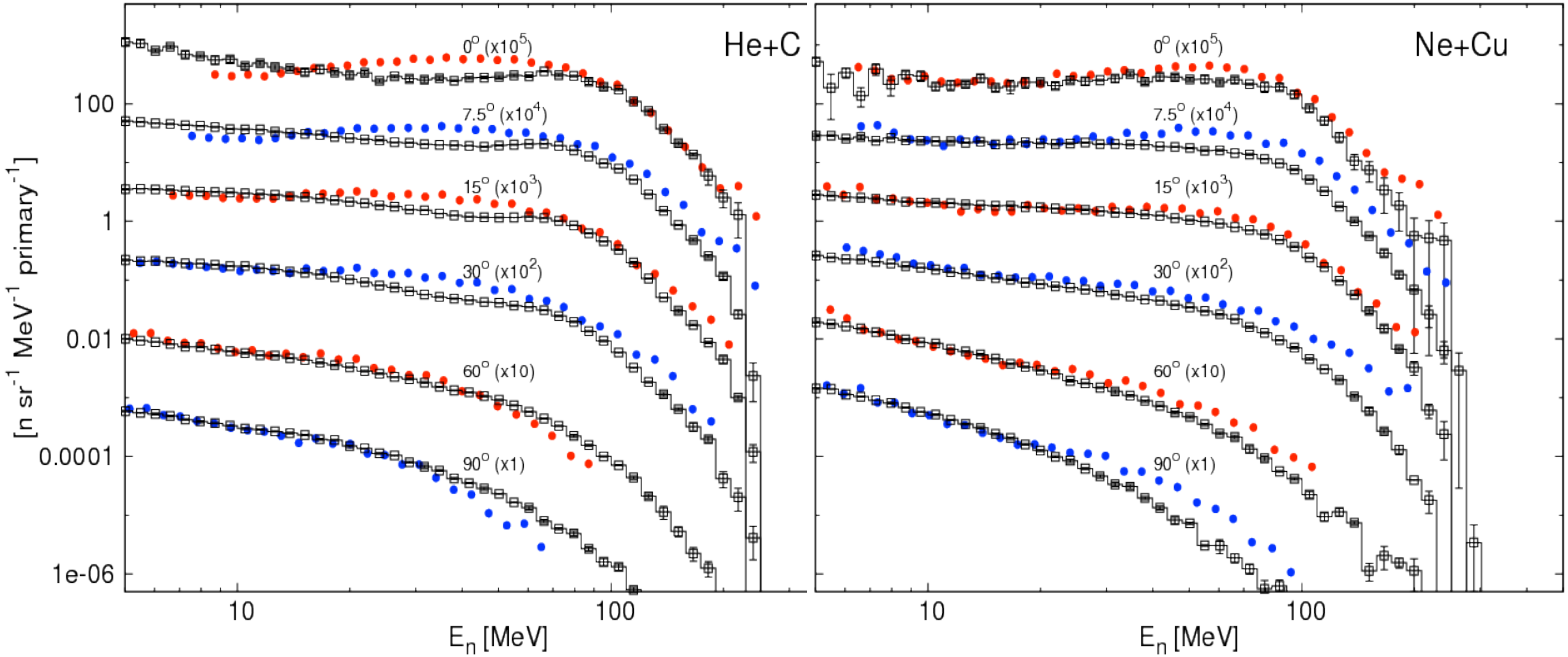


Fragment charge cross section for 1.05 GeV/n Fe ions on Al (left) and Cu (right).

«: FLUKA, i : PRC 56, 388 (1997), o : PRC42, 5208 (1990), Δ: PRC 19, 1309 (1979)

BME: Benchmarking

Double differential neutron yields from 100 MeV/n beams on thick targets



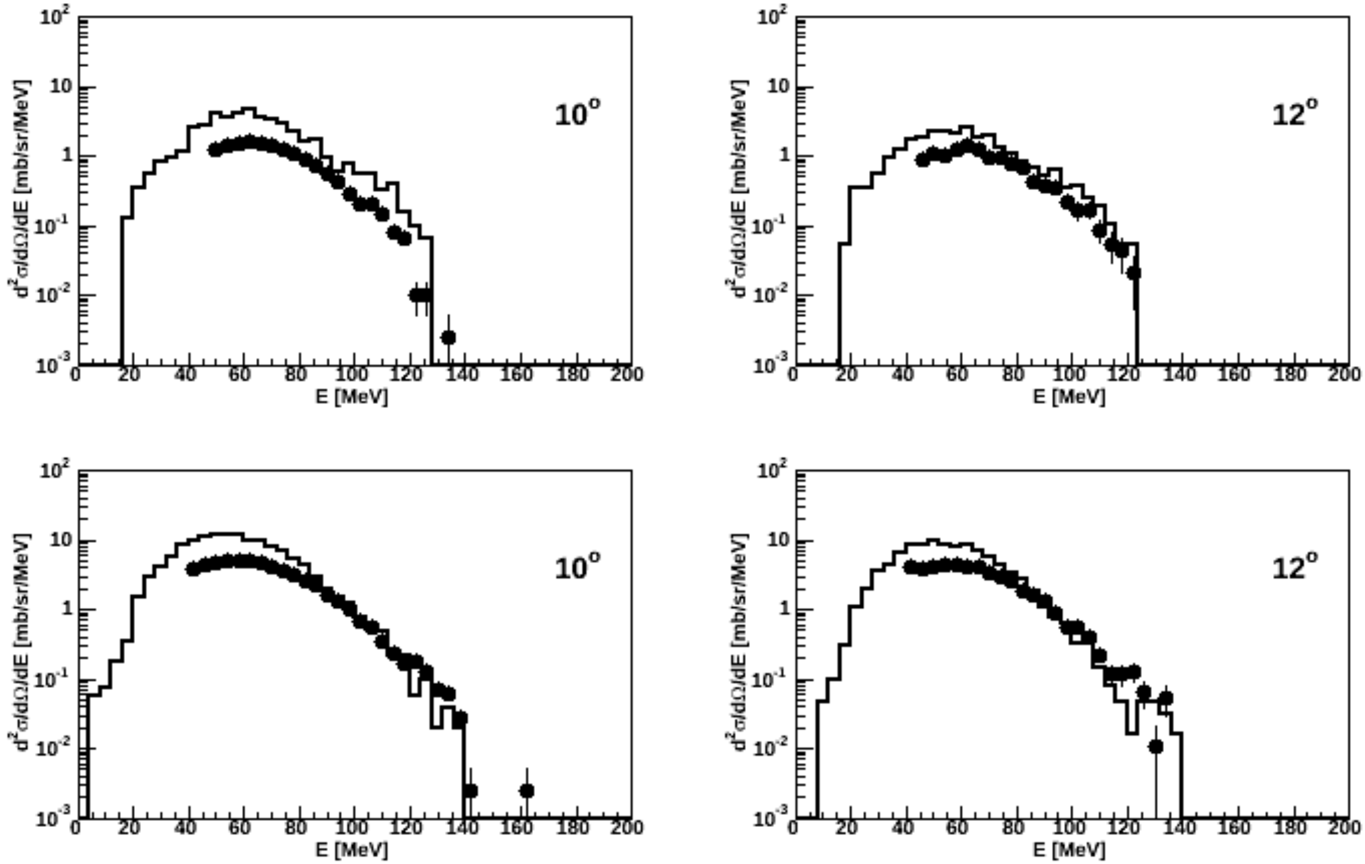
FLUKA vs experimental data from T. Kurosawa, N. Nakao, T. Nakamura et al., Nucl. Sci. Eng. 132, 30 (1999)

BME: Benchmarking

Double differential fragment spectra from C+C at 13 MeV/n

Fluorine

Oxygen



experimental data by courtesy of S. Fortsch et al., iThemba Labs, South Africa

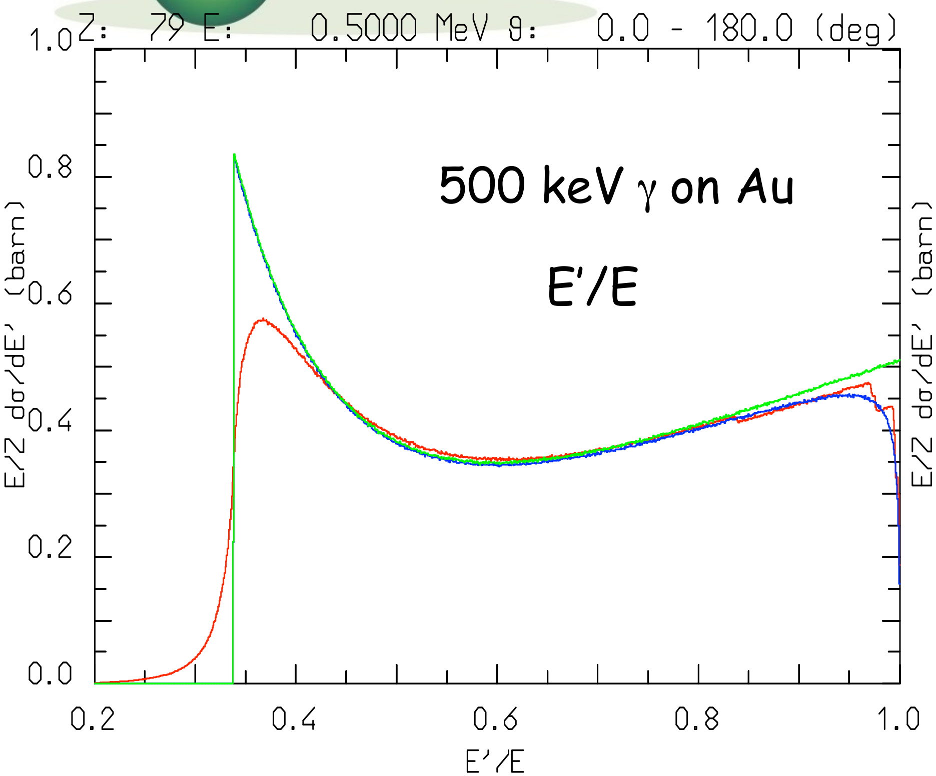
EMF ElectroMagneticFluka

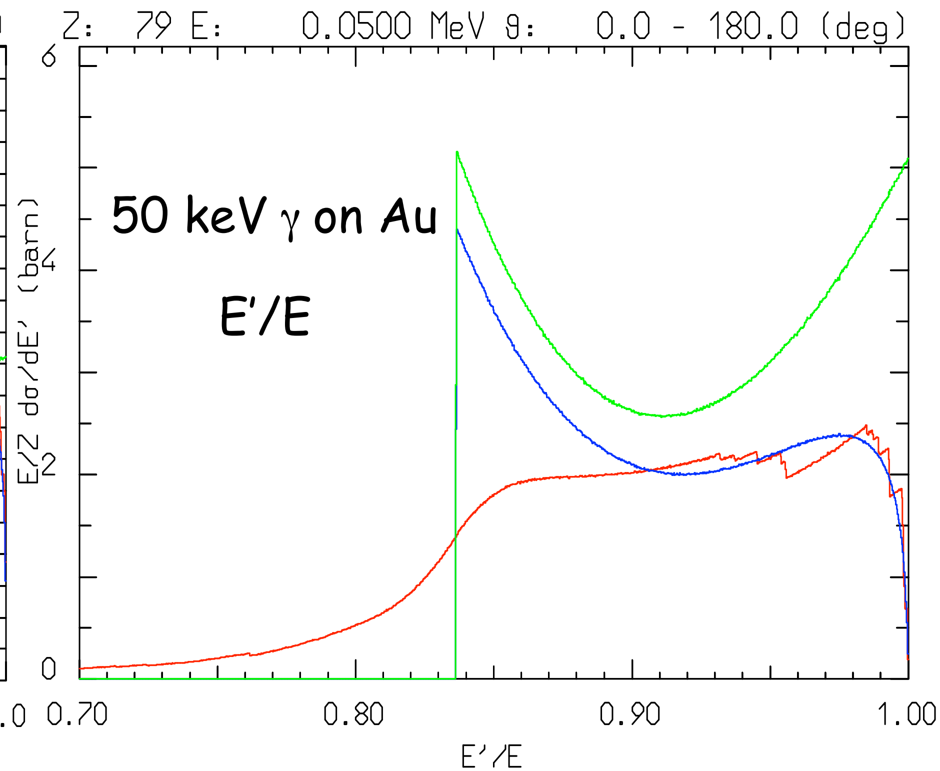
- Photoelectric : fluorescence, angular distribution, Auger, polarization
- Compton and Rayleigh: atomic bonds, polarization
- Pair production: LPM, correlated angular and energy distribution; also $\mu \rightarrow e^+e^-$, $\gamma \rightarrow \mu^+\mu^-$
- Photonuclear interactions; also for μ
- Bremsstrahlung : LPM, angular distribution; also for μ
- Bhabha and Møller scattering
- Positron annihilation at rest and in flight
- μ^- capture at rest, in competition with decay
- Optical photon (Cherenkov) production and transport

Compton and Rayleigh scattering

- Account for atomic bonds using inelastic Hartree-Fock form factors (very important at low E in high Z materials)
- Recent improvement: Compton with atomic bonds and orbital motion (as a better alternative to form factors)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence
- Account for effect of photon polarization

Compton profile examples





green = free electron

blue = binding with form factors

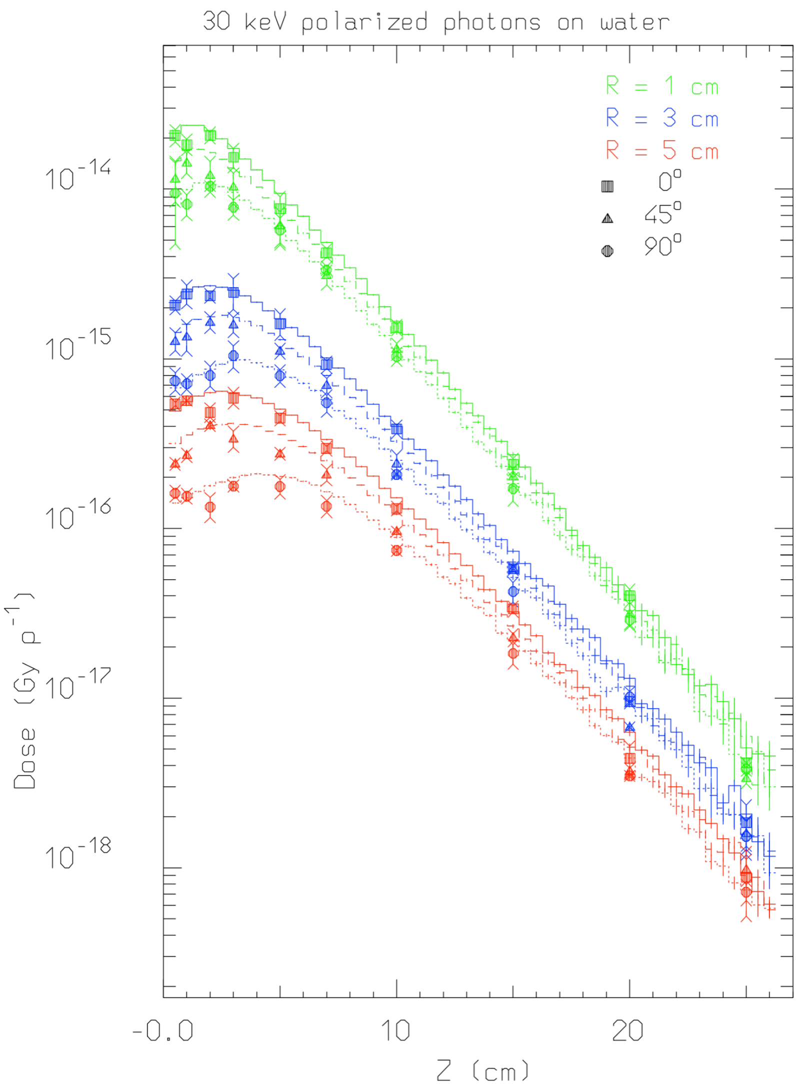
red =binding with shells and orbital motion

Larger effect at very low energies (where, however, the dominant process is photoelectric)

Visible: shell structure near E'=E, smearing from motion at low E'

Polarization

Effect of photon polarization



Deposited dose by 30 keV photons in water

- at 3 distances from beam axis
- as a function of penetration depth
- for 3 orientations with respect to the polarization direction

Pair Production

- Angular and energy distribution of e^+,e^- described correctly (no "fixed angle" or similar approximation)
- No approximations near threshold
- Differences between emitted e^+ and e^- at threshold accounted for
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect

Photonuclear interactions

Photon-nucleus interactions in FLUKA are simulated over the whole energy range, through different mechanisms:

- Giant Resonance interaction (special cross section database)
- Quasi-Deuteron effect
- Delta Resonance production
- Vector Meson Dominance ($\gamma \equiv \rho, \Phi$ mesons) at high energies

Nuclear effects on the **initial state** (i.e. Fermi motion) and on the **final state** (reinteraction /emission of reaction products) are treated by the FLUKA hadronic interaction model (PEANUT)

➔ INC + pre-equilibrium + evaporation/fission/breakup

The (small) photonuclear interaction probability can be enhanced through biasing

Photonuclear interactions: benchmark

Reaction:

$^{208}Pb(\gamma,x\ n)$

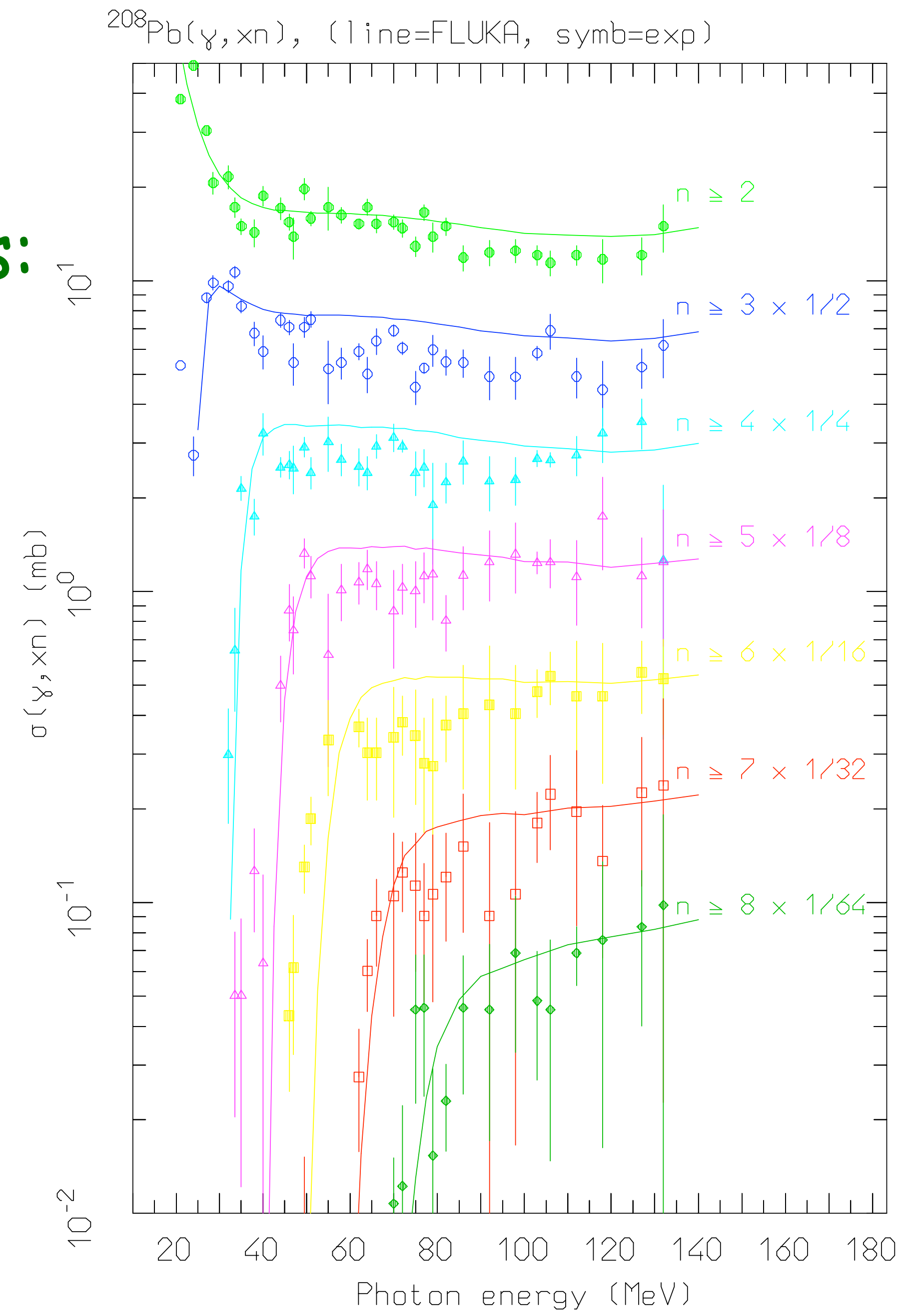
$20 \le E_\gamma \le 140$ MeV

Cross section for multiple neutron emission as a function of photon energy, Different colors refer to neutron multiplicity $\ge$ n , with $2 \le n \le 8$

Symbols: experimental data

NPA367, 237 (1981)

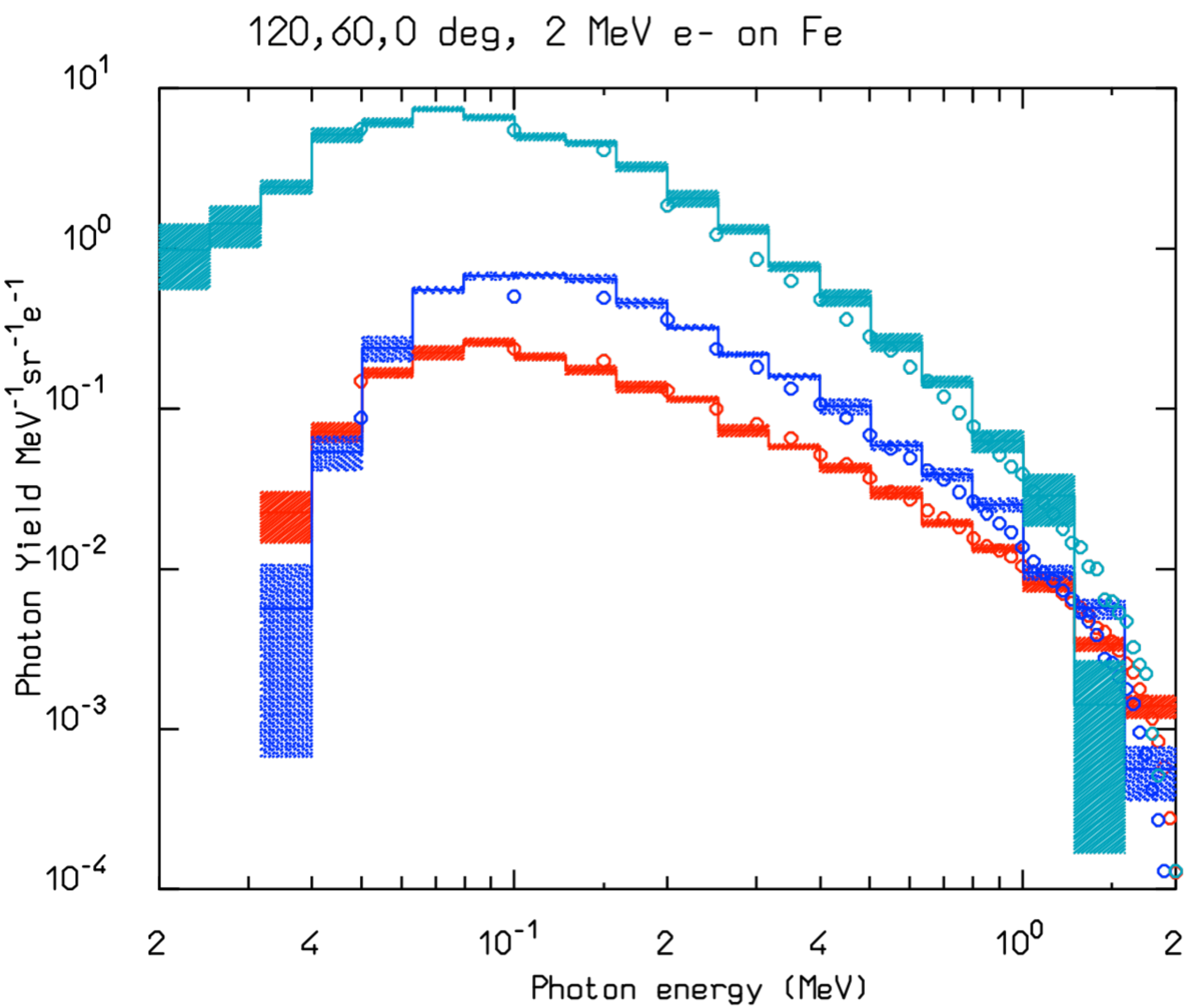
NPA390, 221 (1982)



Bremsstrahlung

- Energy-differential cross sections based on the Seltzer and Berger database, interpolated and extended:
  - to a finer energy mesh
  - to larger energies (1000 TeV, taking into account the LPM effect)
- Finite value at tip energy
- Soft photon suppression (Ter-Mikaelyan) polarization effect
- Special treatment of positron bremsstrahlung with ad hoc spectra at low energies
- Detailed photon angular distribution <u>fully correlated to energy</u>

Bremsstrahlung: benchmark



2 MeV electrons on Iron,

Bremsstrahlung photon spectra

measured (dots)

and

simulated (histograms)

at three different angles

Other $e^{\pm}$ interactions

Positron Annihilation

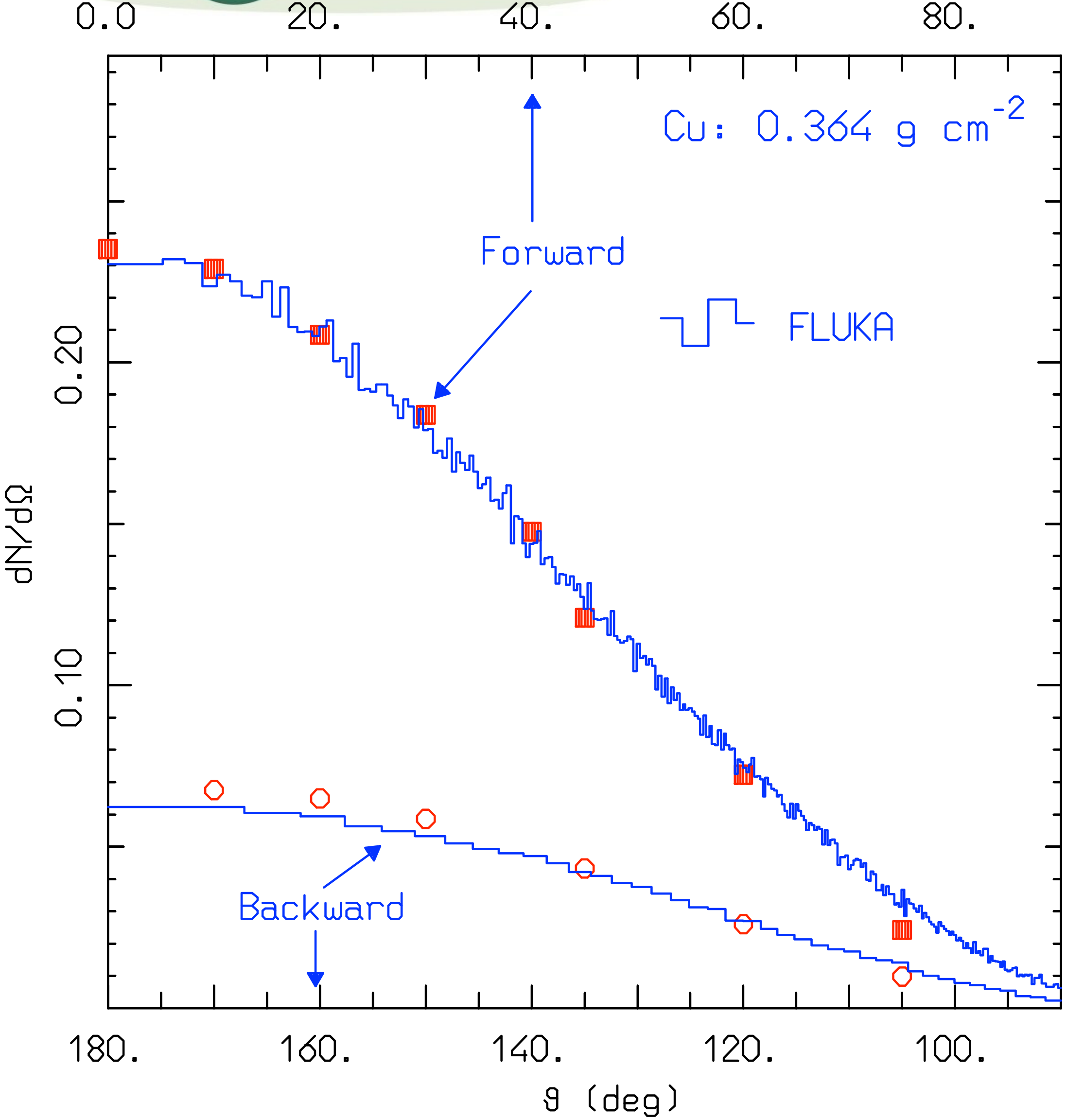
- At rest and in flight according to Heitler
- In annihilation at rest, account for mutual polarization of the two photons
- In preparation: non-collinearity of photons due to Fermi motion of electrons

Scattering

- e^+ : Bhabha
- e^- : Møller

- Special multiple-scattering treatment (also for heavier charged particles)
- Single-scattering transport on request

Electron scattering: benchmark



Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm^2 thick Copper foil

Measured (dots) and simulated (histograms) data

Bremsstrahlung and pair production by muons and charged hadrons

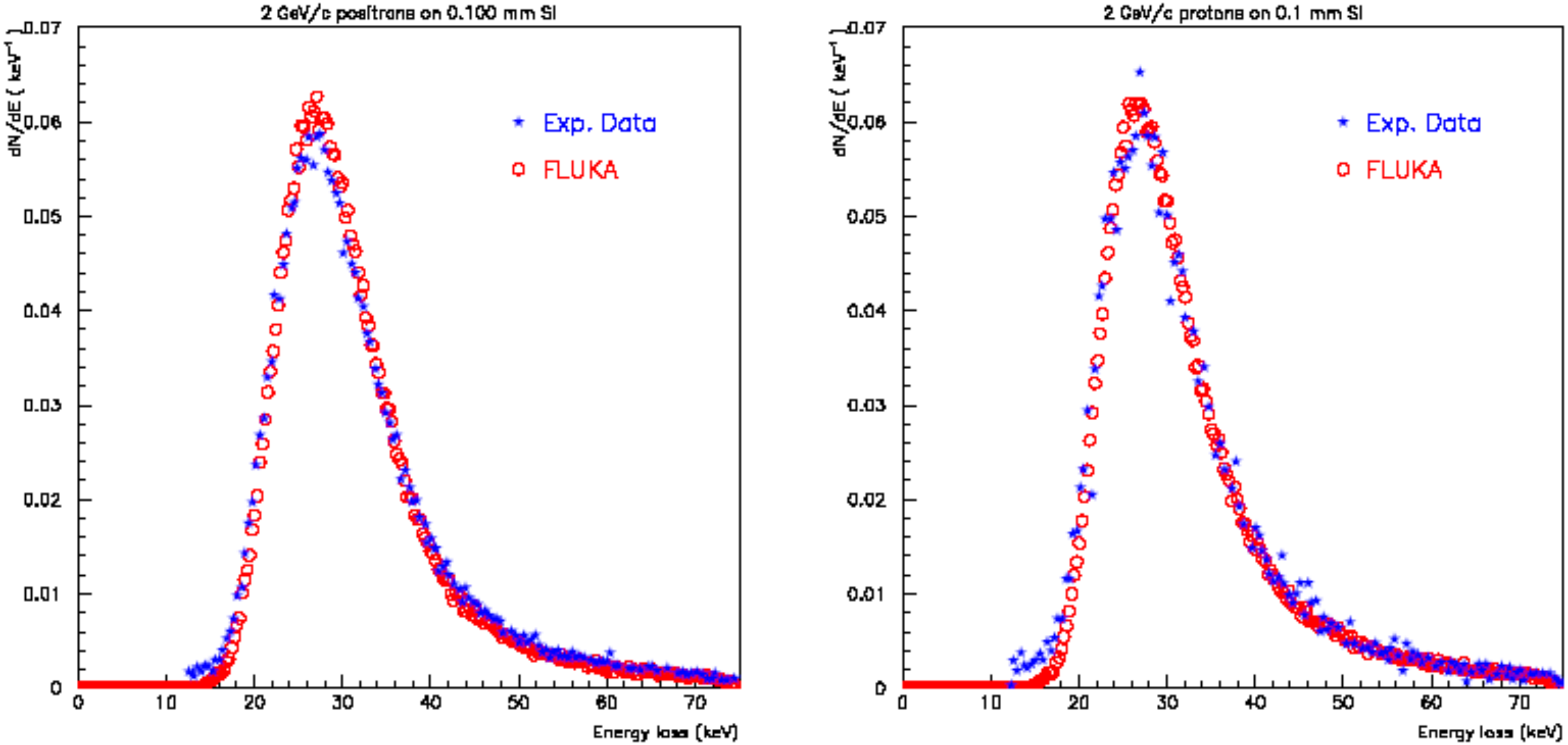
- At high energies, bremsstrahlung and pair production are important also for muons and charged hadrons. For instance, in Lead the muon energy loss is dominated by these processes above 300 GeV.

  Bremsstrahlung: implemented in FLUKA including the effect of nuclear form factors
- The user can set an energy threshold for the activation of these processes.
- Above the threshold, the processes are described in detail, with explicit γ and $e^{\pm}$ production.
- Below threshold, energy loss is accounted for in a continuous approximation

Ionization fluctuations

Below δ-ray threshold, new original approach:

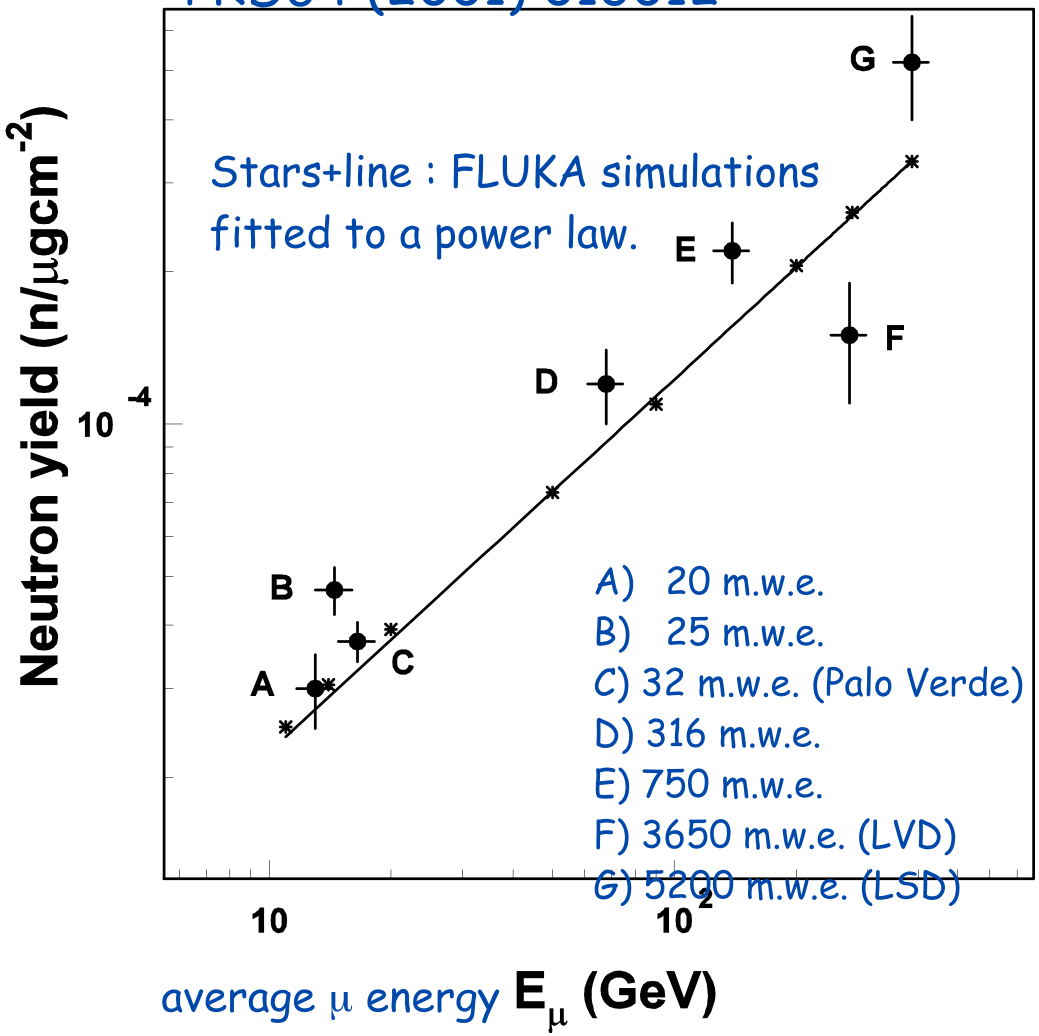
Cumulants of Poisson distribution convoluted with $d\sigma/dE$

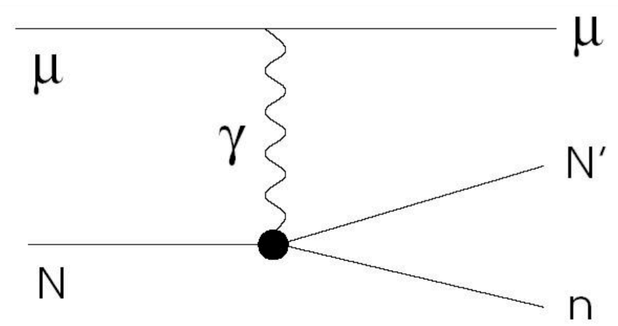


Experimental and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100 μm of Si J.Bak et al. NPB288, 681 (1987)

Muon-induced neutron background in underground labs

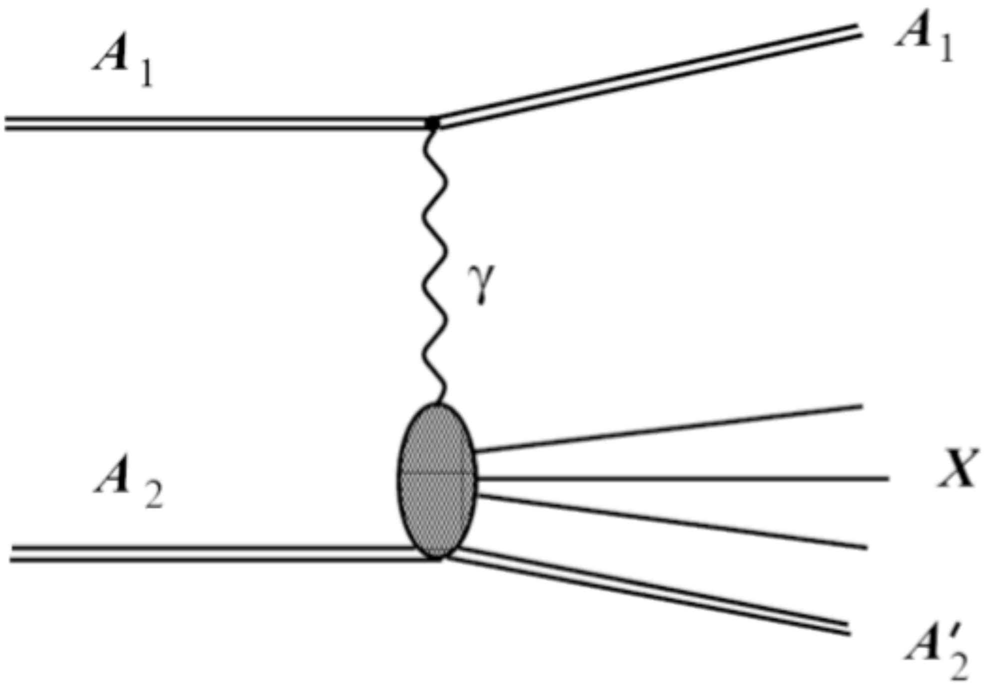
PRD64 (2001) 013012





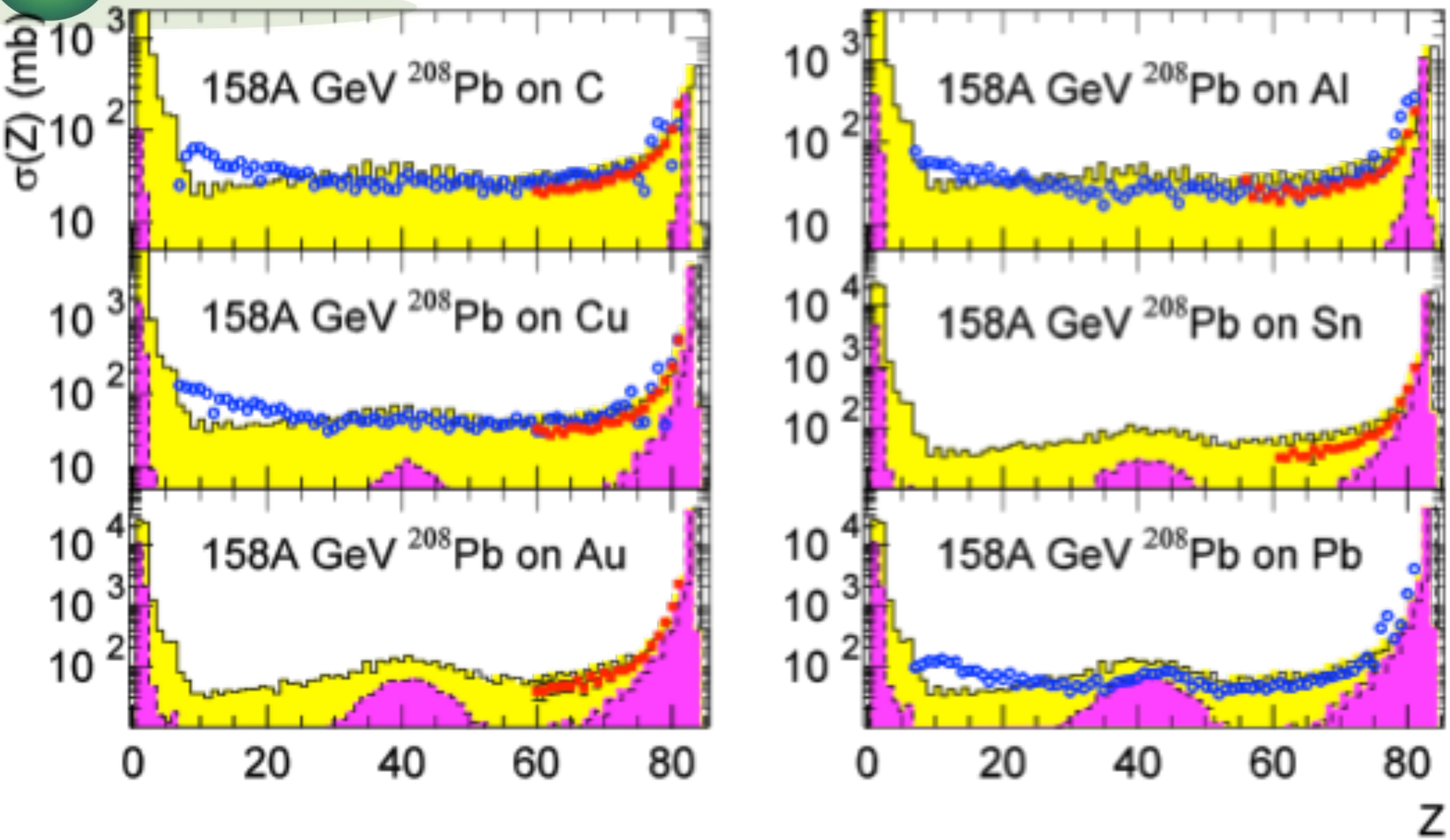
- Cross section factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction.
- Nuclear screening taken into account.
- Only Virtual Meson Interactions modeled, following the FLUKA meson-nucleon interaction models.
- Nuclear effects are the same as for hadron-nucleus interactions

Electromagnetic dissociation of heavy ions



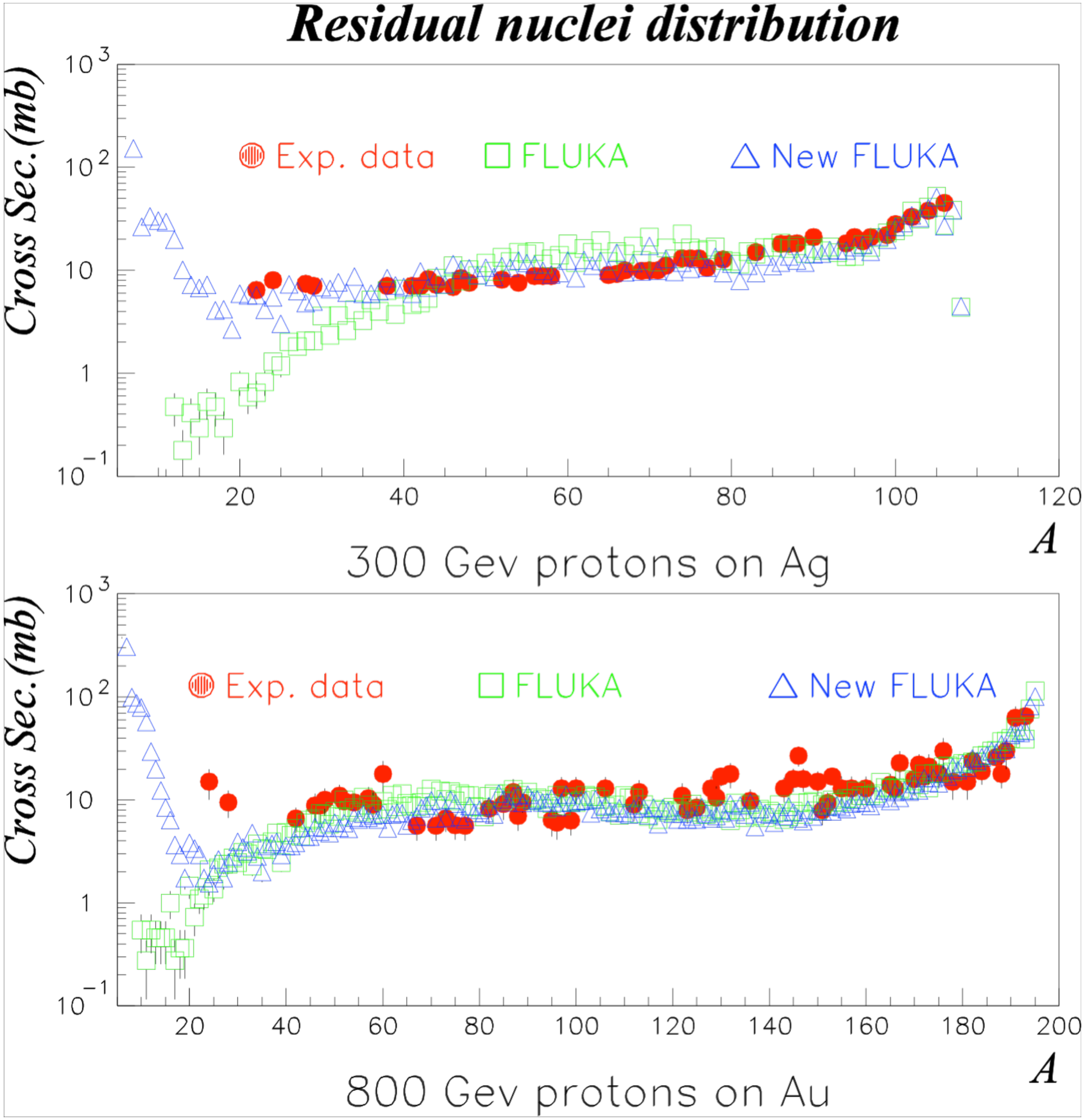
$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega)\sigma_{\gamma A_2}(\omega), \qquad n_{A_1}(\omega) \propto Z_1^2$$

158 GeV/n Pb ion fragmentation



Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), yellow histos are FLUKA (with DPMJET-III) predictions: purple histos are the electromagnetic dissociation contribution

Residual nuclei



Data from:

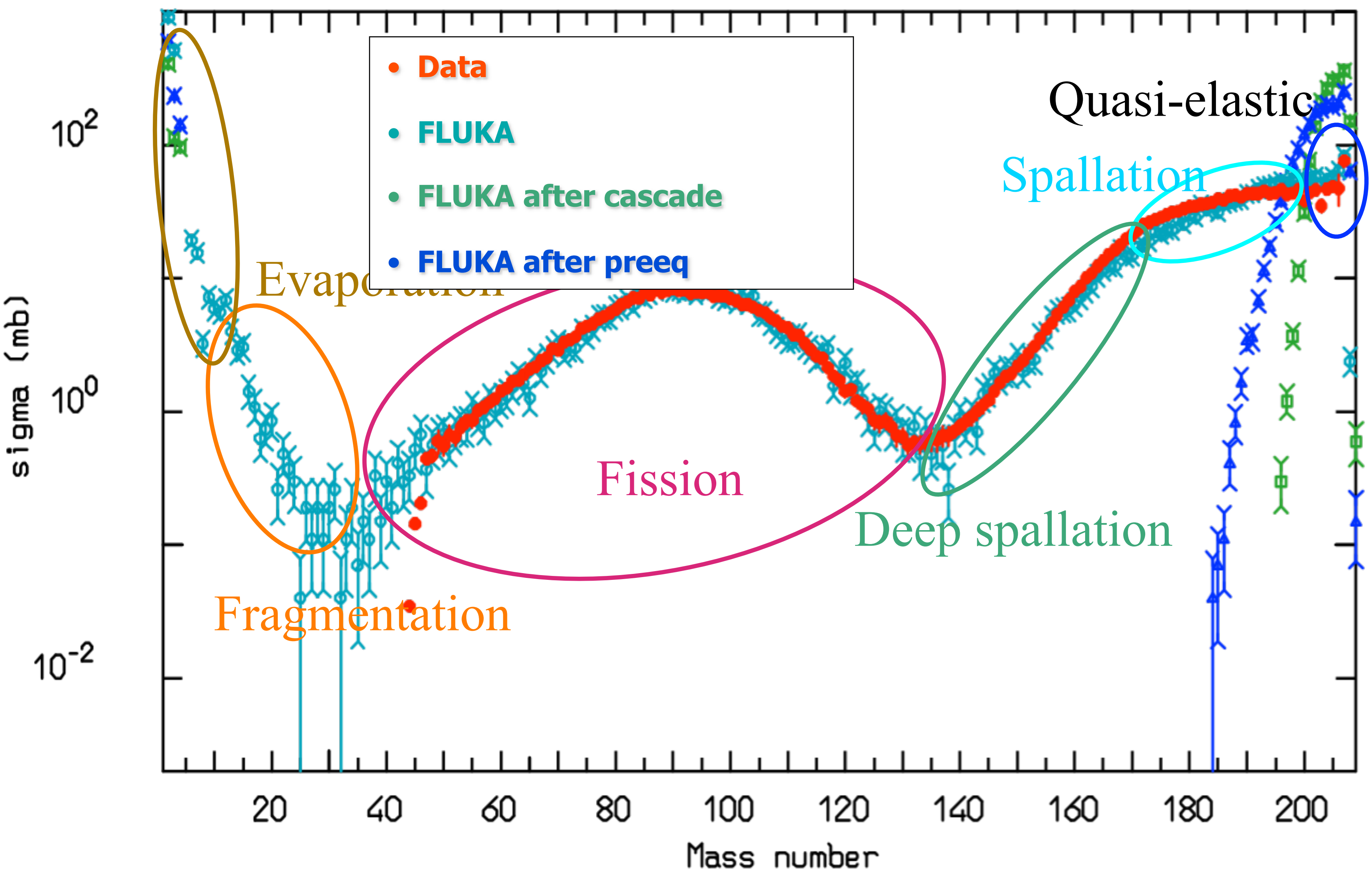
Phys. Rev. C19 2388 (1979) and

Nucl. Phys. A543, 703 (1992)

Also for A-A interactions

Residual nuclei

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



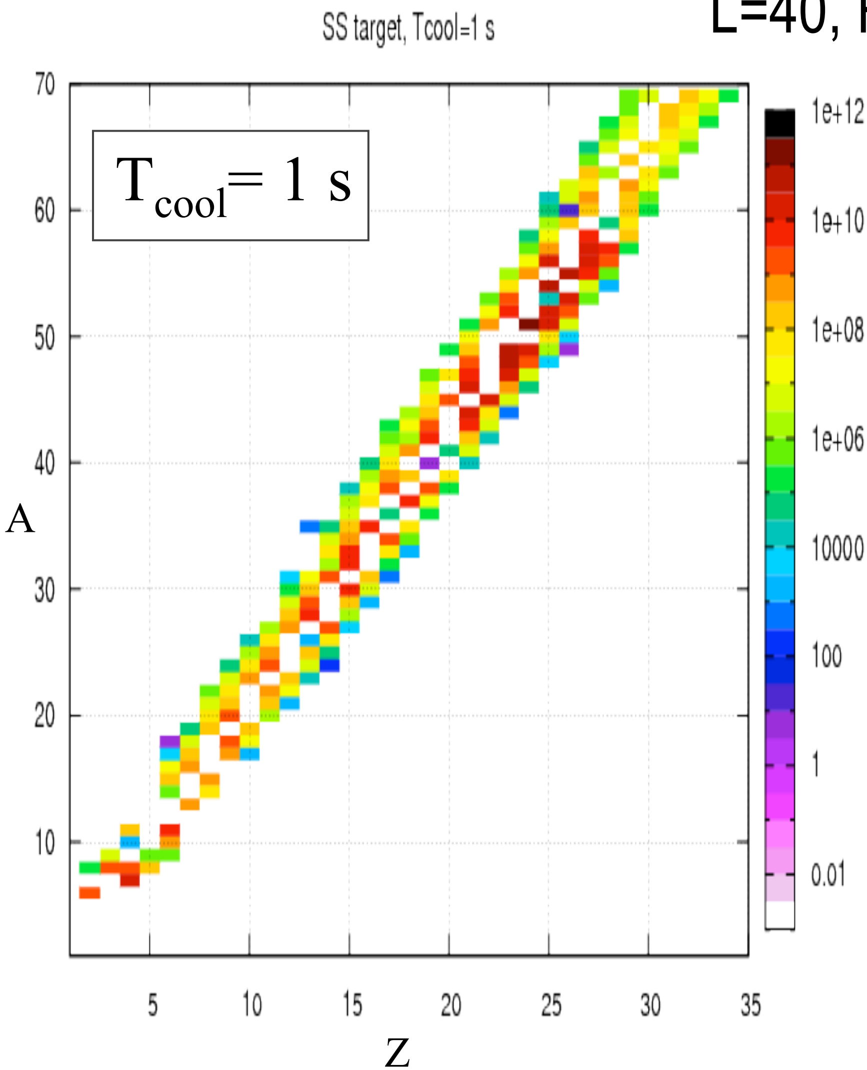
Online evolution of activation and residual dose

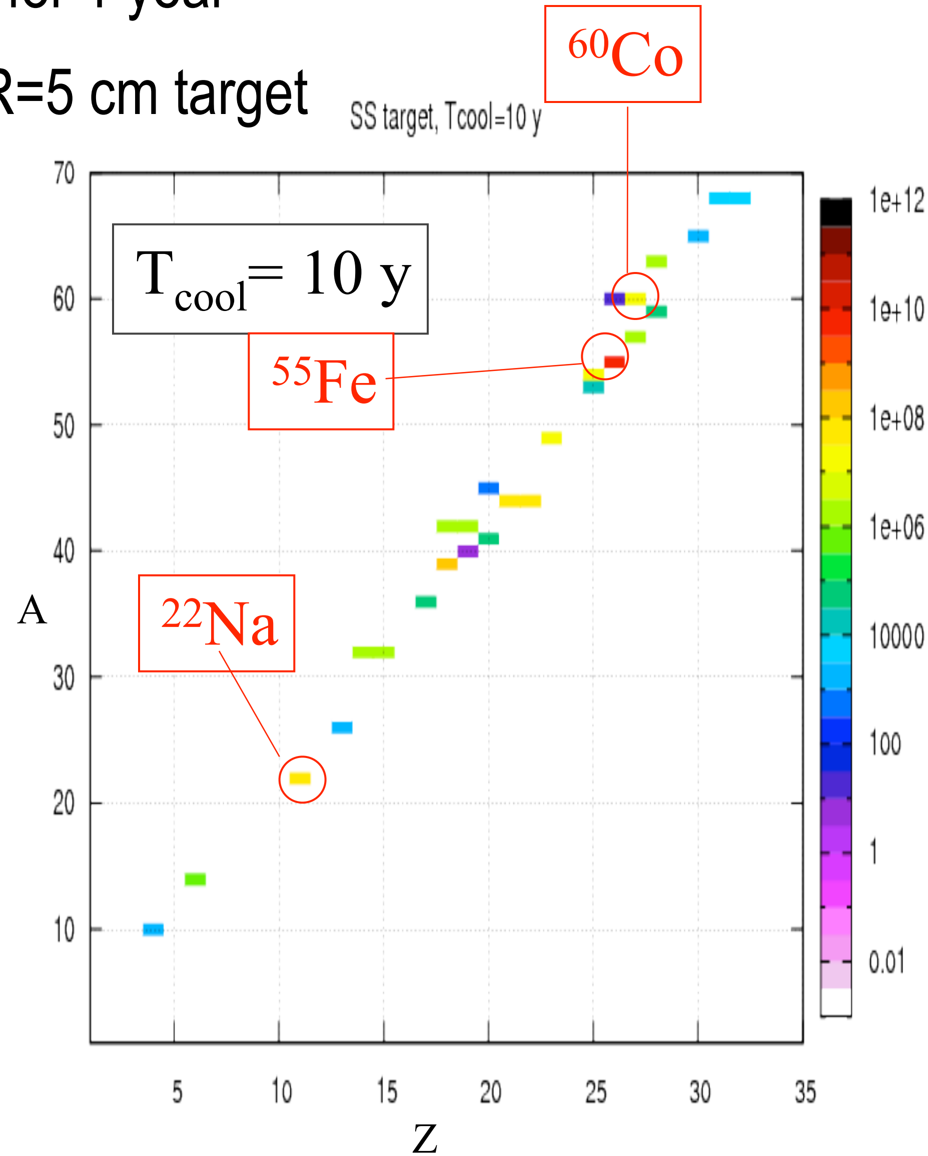
- Decay β, γ, produced and transported "on line"
  - Screening and Coulomb corrections accounted for $\beta^{+/-}$ spectra
  - Complete database for γ lines and β spectra covering down to 0.1% branching
- Time evolution of induced radioactivity calculated analytically
  - Fully coupled build-up and decay (Bateman equations)
  - Up to 4 different decay channels per isotope
- Results for activity, energy deposition, particle fluence etc, calculated for custom irradiation/cooling down profile

Activity (Bq) evolution after irradiation of a SS sample

10^{12} p/s for 1 year

L=40, R=5 cm target





Benchmark experiment – *Instrumentation*

M. Brugger et al., Radiat. Prot. Dosim. 116 (2005) 12-15

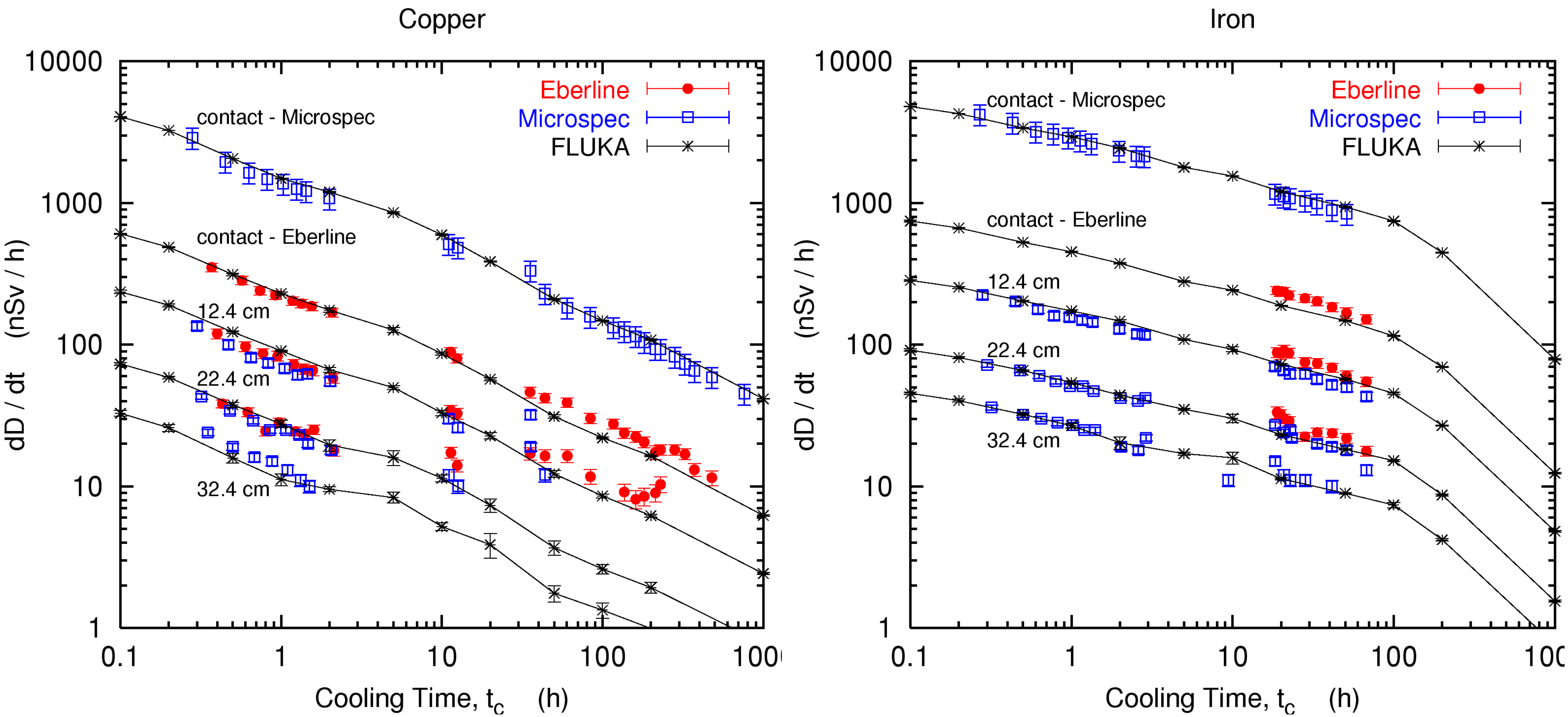
Portable spectrometer Microspec

- NaI detector, cylindrical shape, 5 x 5 cm
- folds spectrum with detector response ("calibrated" with ^{22}Na source)
- physical centre of detector determined with additional measurements with known sources (^{60}Co, ^{137}Cs, ^{22}Na) to be 2.4 cm

Thermo-Eberline dose-meter FHZ 672

- organic Scintillator and NaI detector, cylindrical shape, 9 x 9 cm
- assumes average detector response
- physical centre of detector determined as above to be 7.3 cm

Dose rate from induced activity



Dose rate as a function of cooling time
for different distances between sample and detector
(2 different instruments)

Biasing Techniques

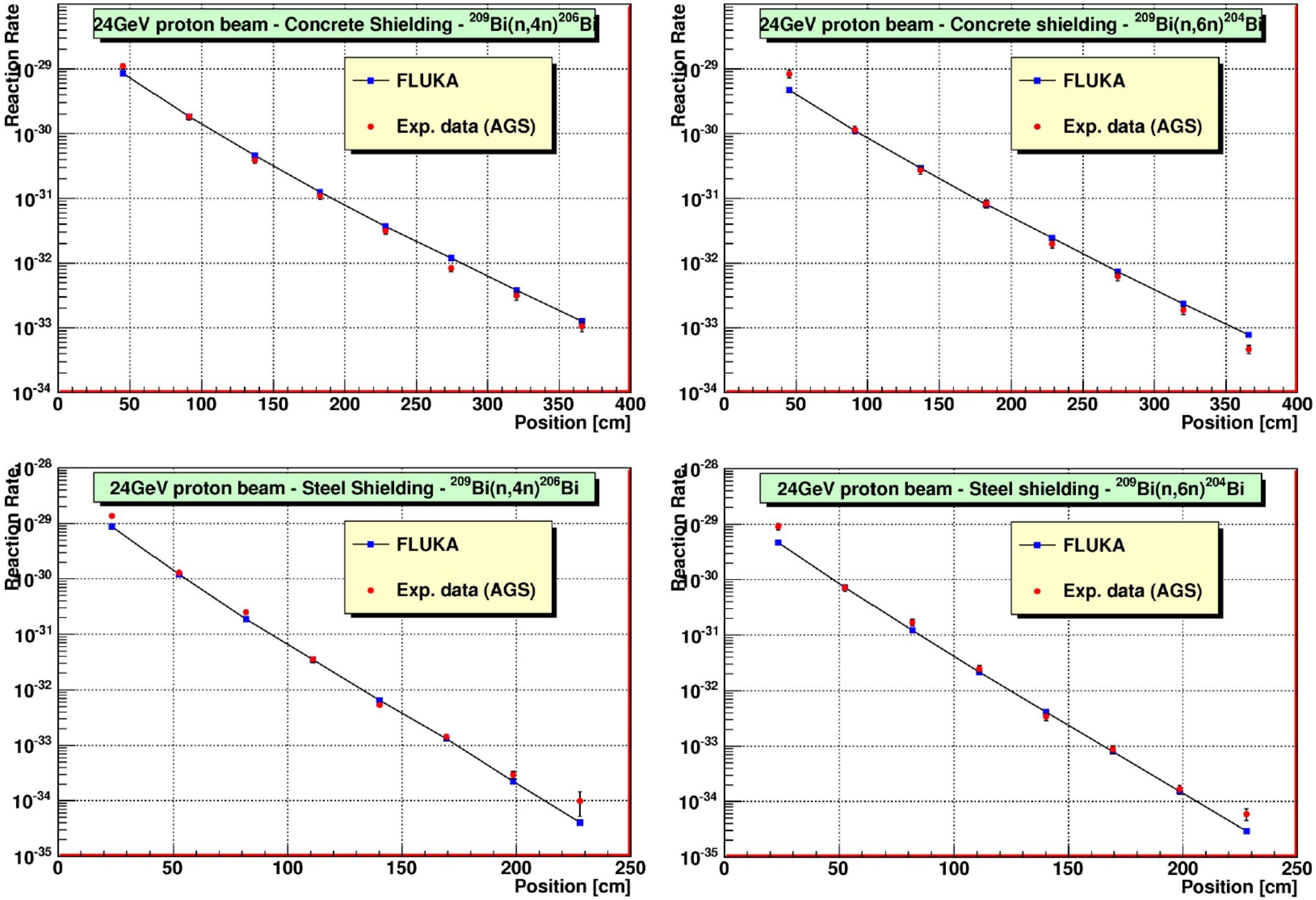
FLUKA offers several possibilities for biasing:

- Importance Biasing
- Weight windows
- Leading Particle Biasing
- Multiplicity Tuning
- Biased downscattering for neutrons, only for experts
- Non-analog neutron absorption
- Biasing mean free paths
- Biasing decay length and direction
- User-defined biasing

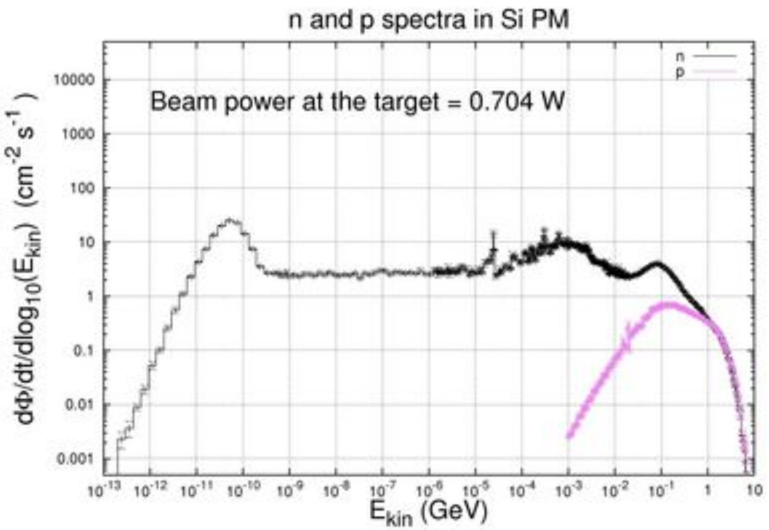
Some examples of applications

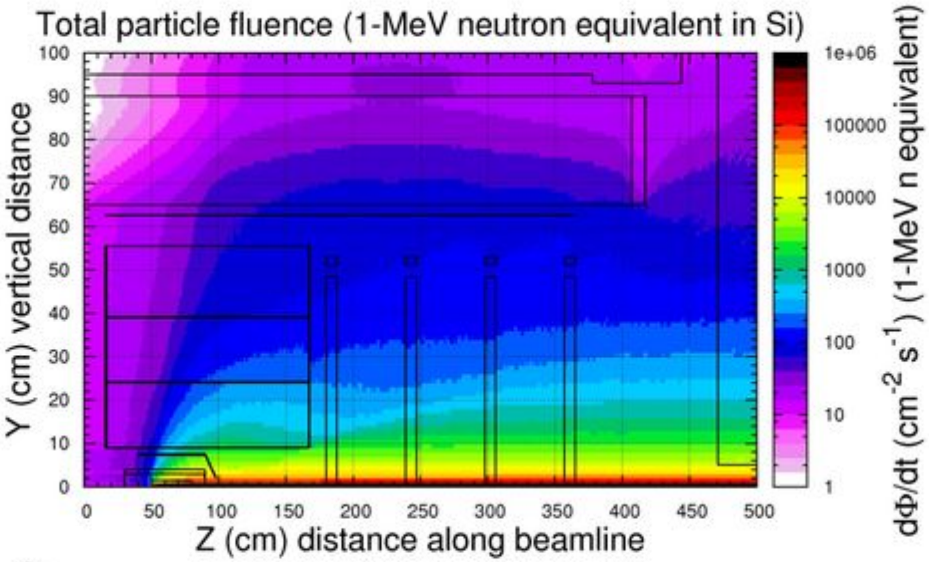
Proton Accelerator Shielding

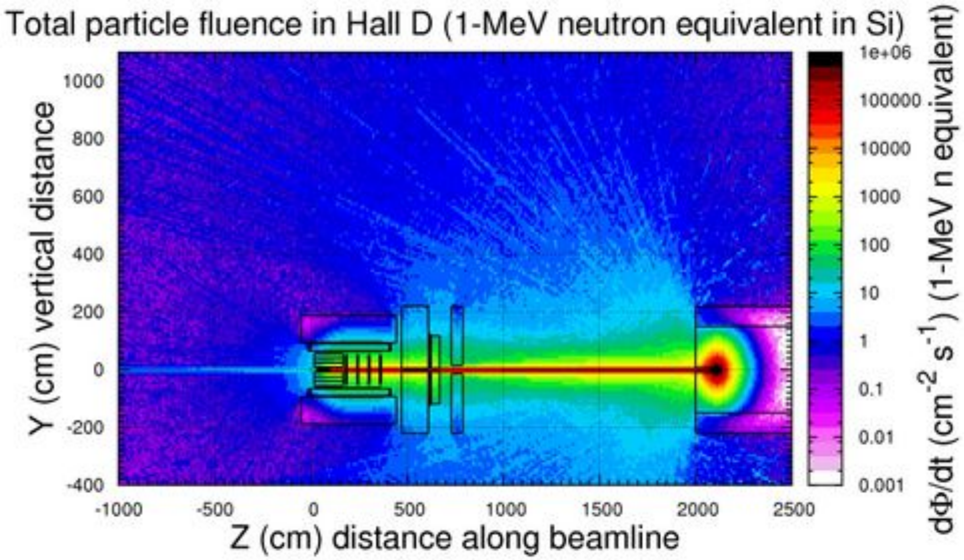
Attenuation benchmark: beam on a Hg target



Predicting radiation damage in GlueX experiment (Jlab Hall D)







FLUKA is extensively used to calculate radiation damage.

Quantities that can be calculated:

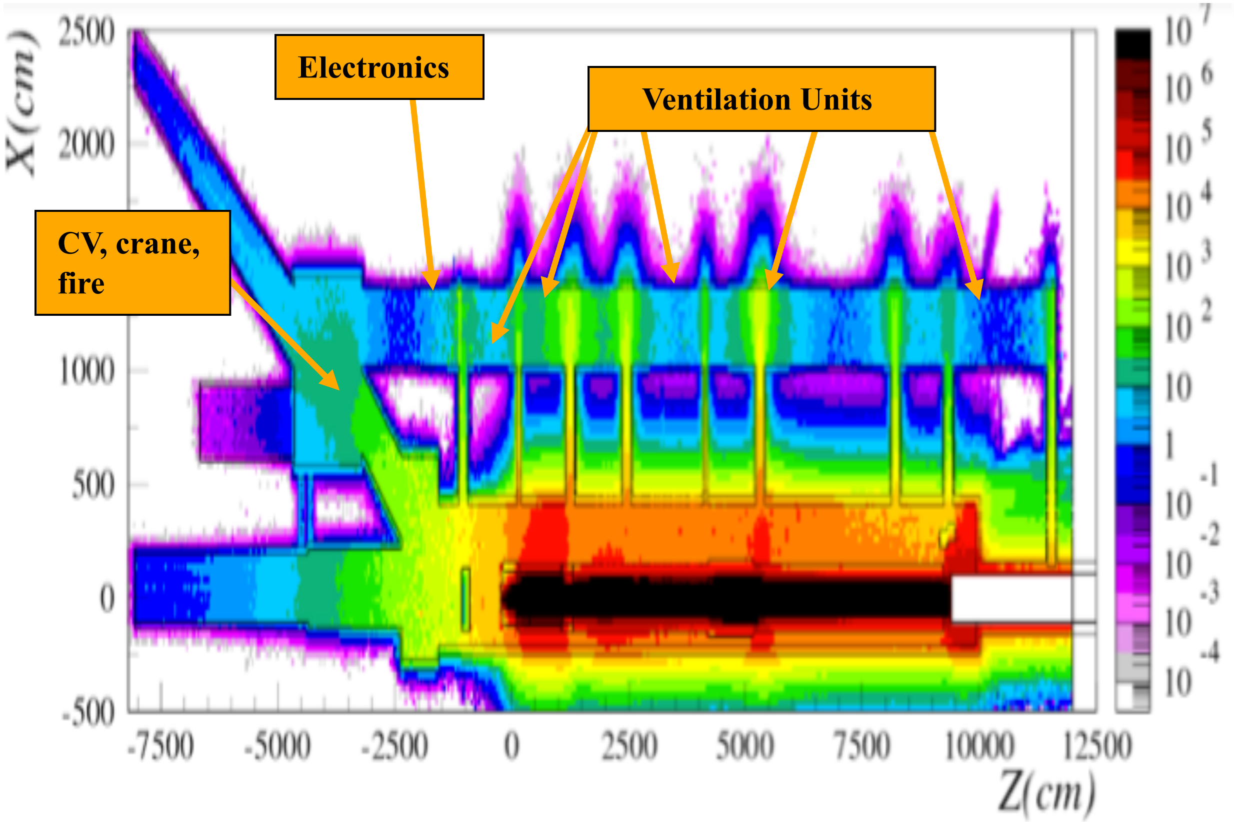
- 1-MeV neutron equivalent fluence in Si
- Hadron fluence with E > 20 MeV (SEU)
- DPAs (Displacements Per Atom)

An example of damage to Electronics:

Cern Neutrino to Gran Sasso

2007 Physics run: Single Event Upsets in ventilation electronics: caused ventilation control failure and interruption of communication

8 10^{17}p.o.t. @ 400 GeV delivered (≈2% of a "CNGS nominal year")



Predicted dose levels in agreement with measurements

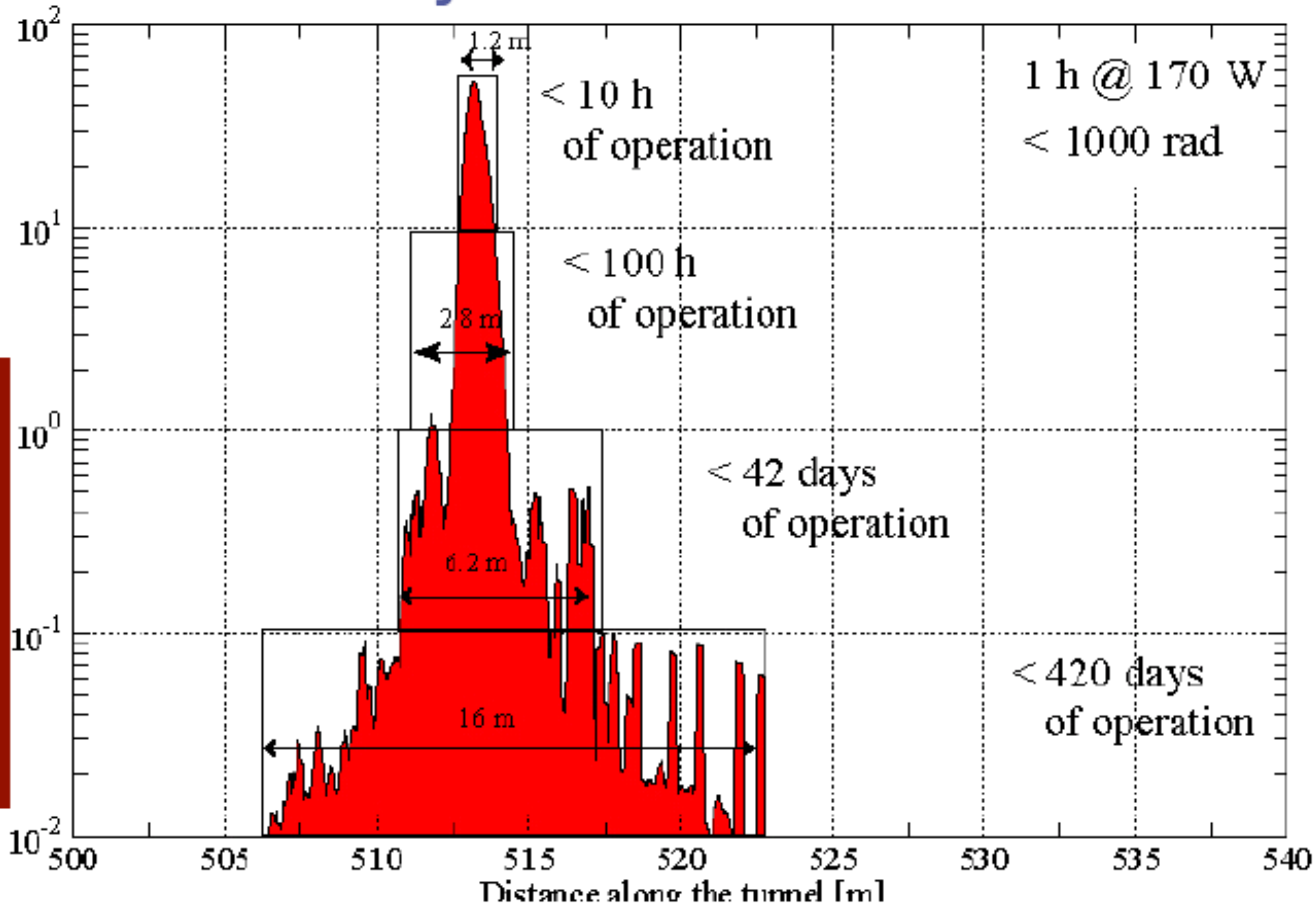
Damage to electronics

SLAC: Damage to electronics near the dumps at the LCLS (Linear Coherent Light Source)

The lifetime of electronic components can be estimated as a function of the distance to major sources of radiation

1-MeV neutron equivalent fluence

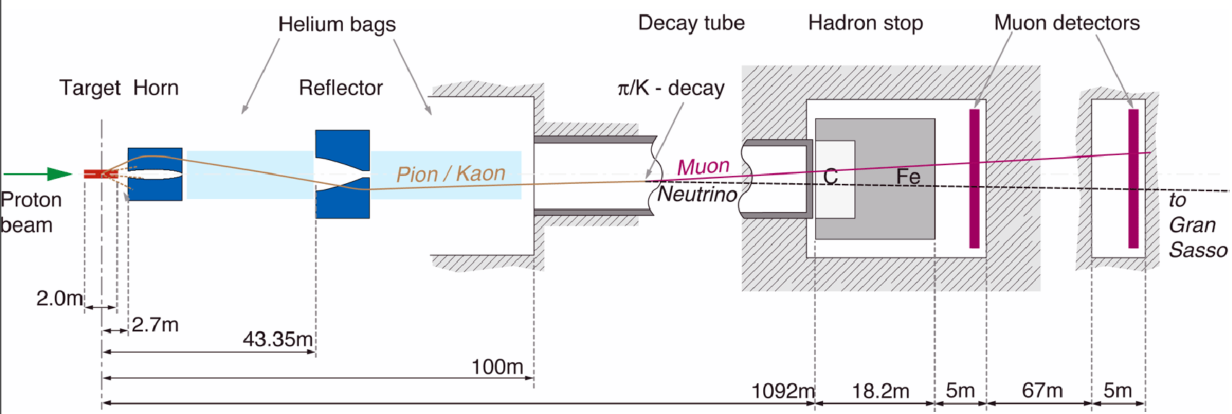
Calculation of lifetime of electronics equipment as a function of the distance to TDUND



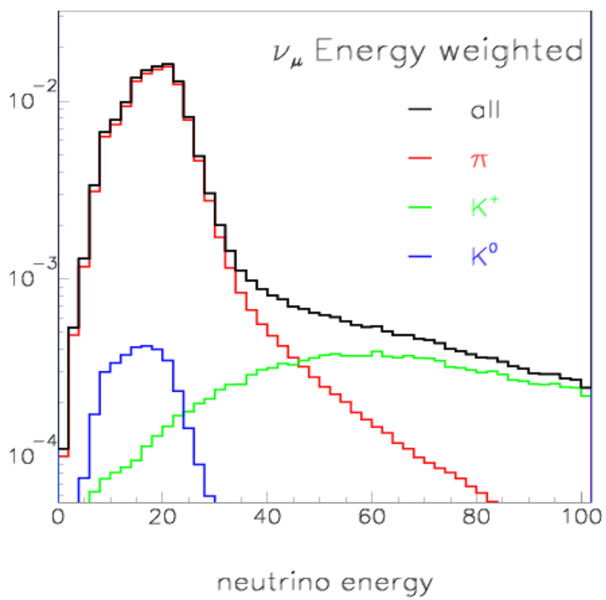
The CERN to Gran Sasso ν beam

FLUKA is the tool which has been used to design CNGS:

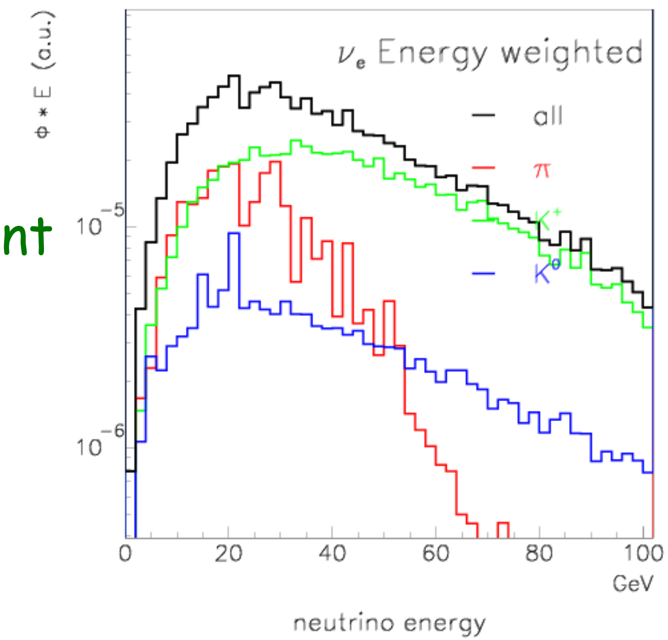
both engineering and physics



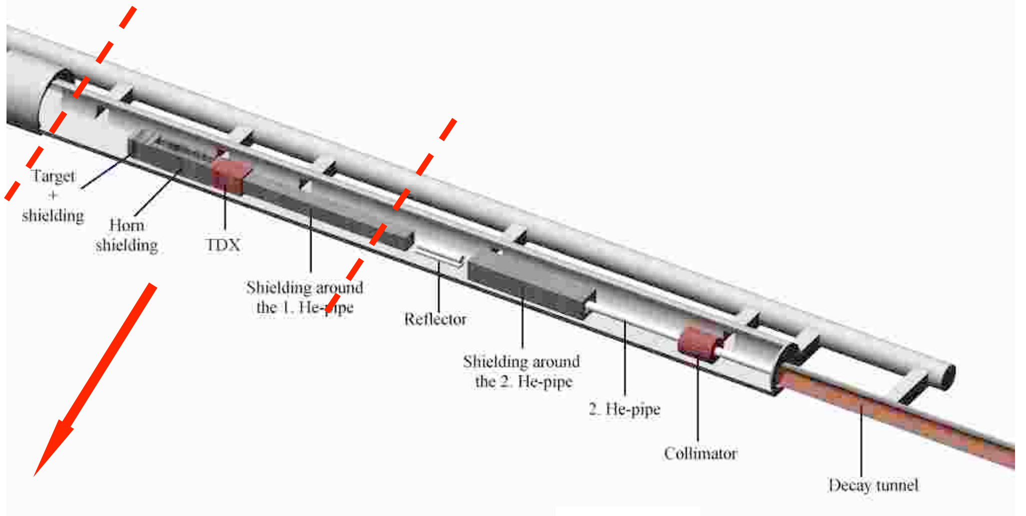
The simulation includes all details of beam transport, interaction, structure of target, horn



Neutrino event spectra at Gran Sasso

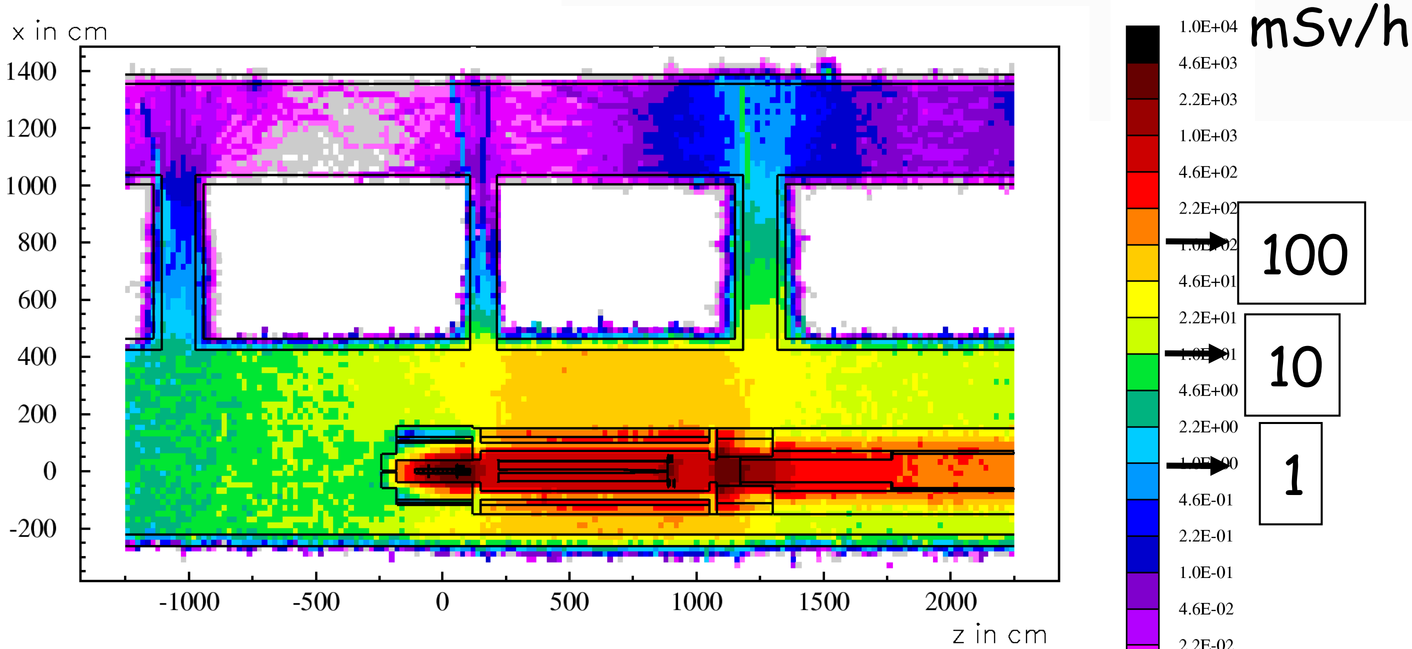


Applications – CNGS



Example:

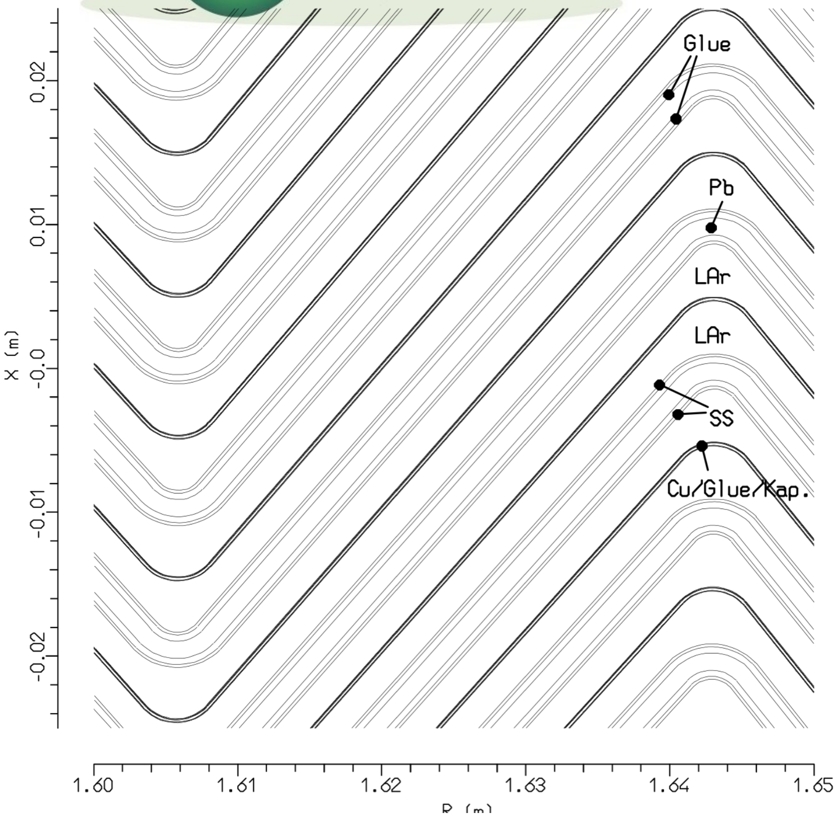
t_{cool} = 1 day

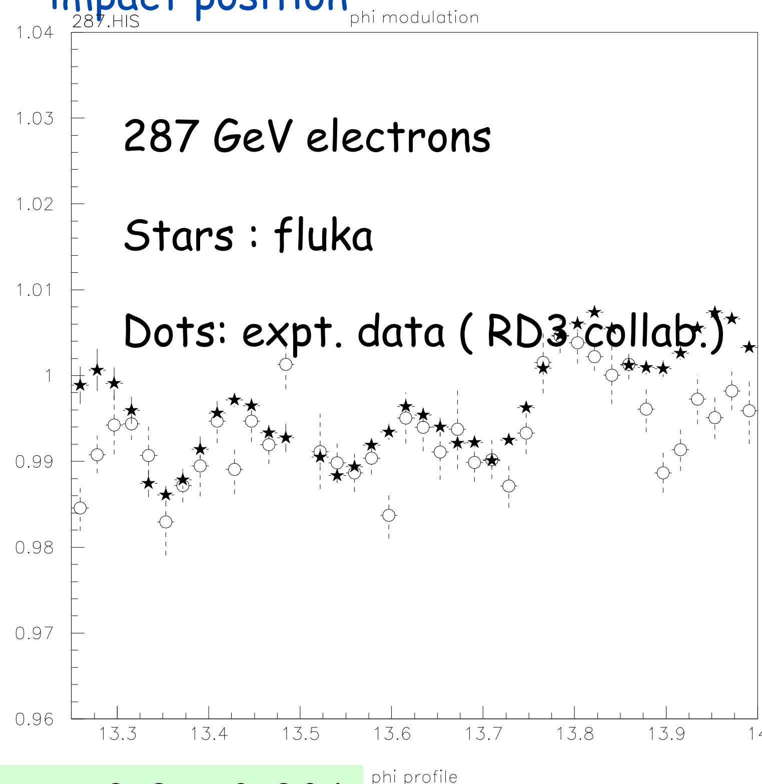


Residual Dose Equivalent Rate (mSv/h)
200 days irradiation, 1 day cooling
8×10^{12} protons/s

A high energy E-M example

The Atlas "accordeon" EM calorimeter: detail of the FLUKA geometry and modulation of response vs. electron impact position





Energy resolution 10-100 GeV:

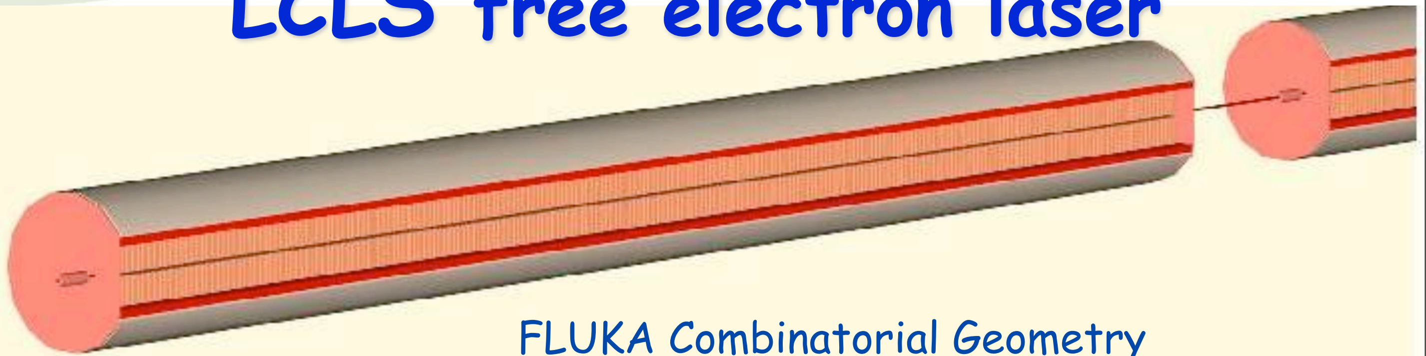
$$Exp : \frac{\sigma}{E} = \frac{9.8 \pm 0.4\%}{\sqrt{E}}$$

$$Fluka : \frac{\sigma}{E} = \frac{9.2 \pm 0.3\%}{\sqrt{E}}$$

Radiation damage in permanent magnets

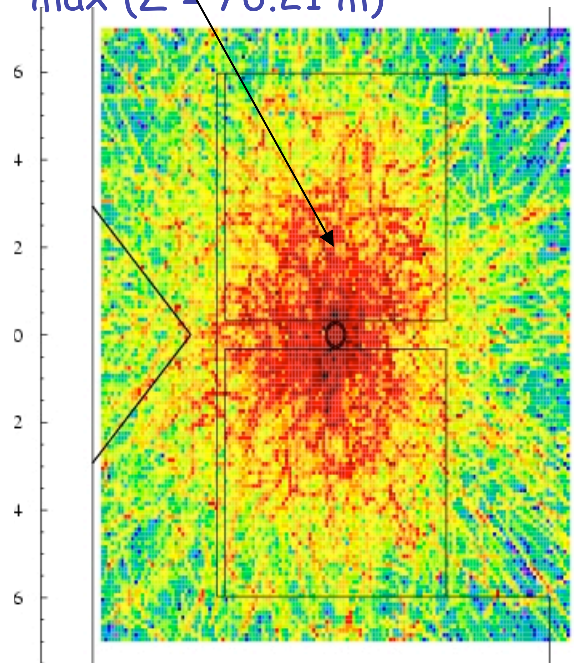
LCLS free electron laser

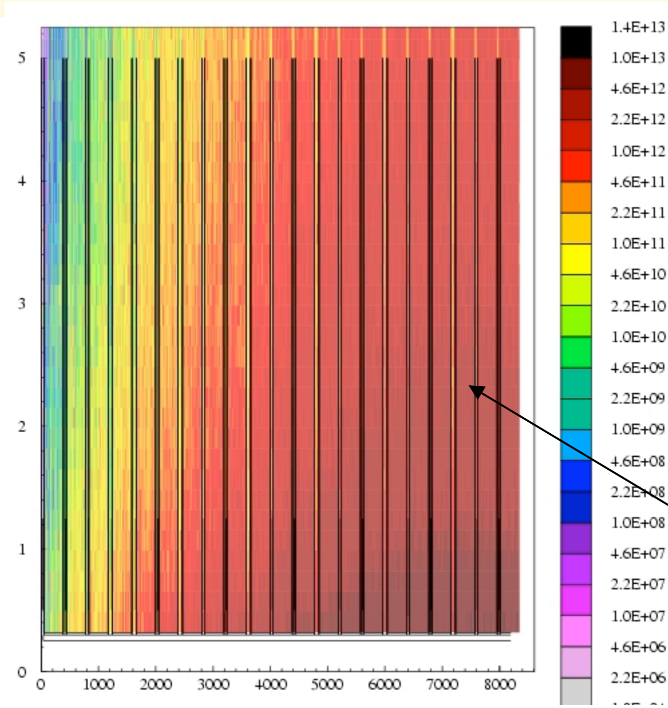
Neutron fluence distribution

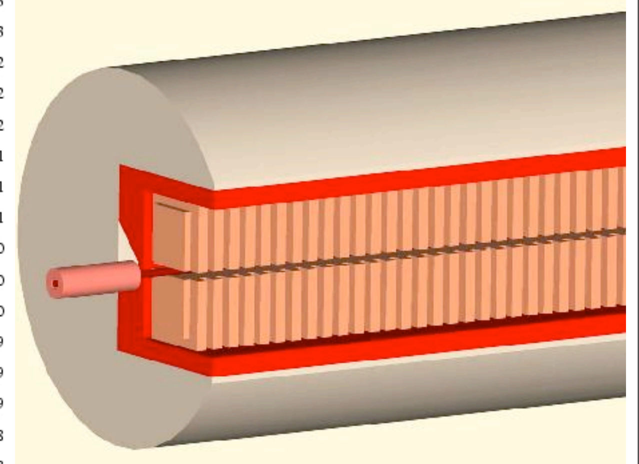


FLUKA Combinatorial Geometry

Transverse section of the magnets at fluence max (Z = 76.21 m)







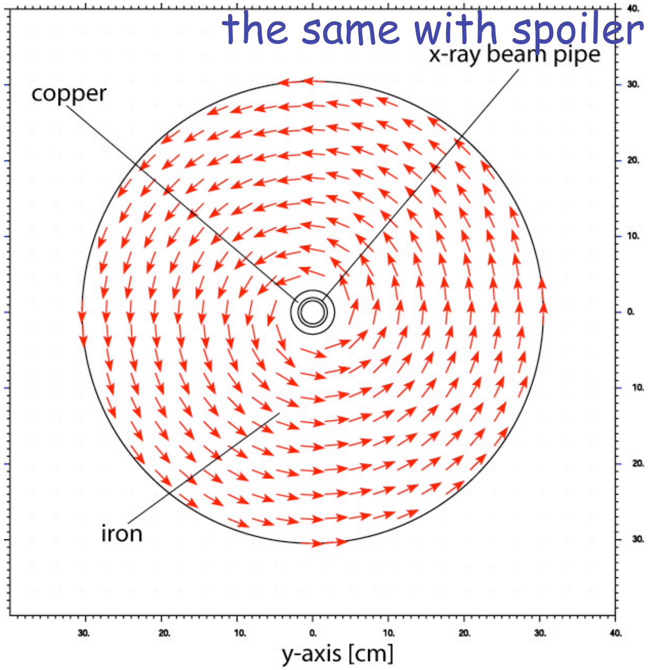
Longitudinal section (83 m long, 5 cm high)

Effect of a magnetic muon spoiler in the LCLS tunnel

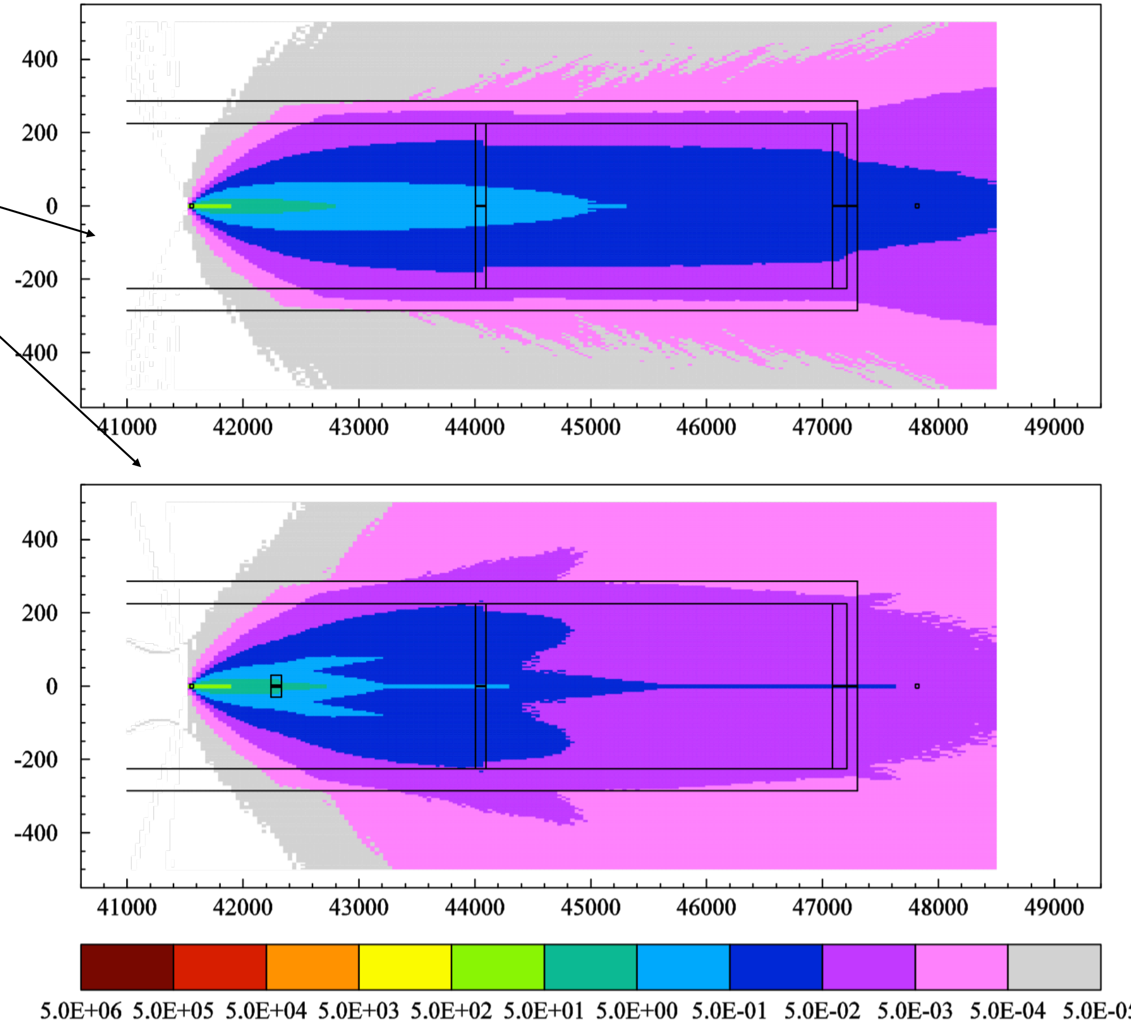
The spoiler allows to reduce the shielding thickness in the forward direction.

dose rate map without spoiler

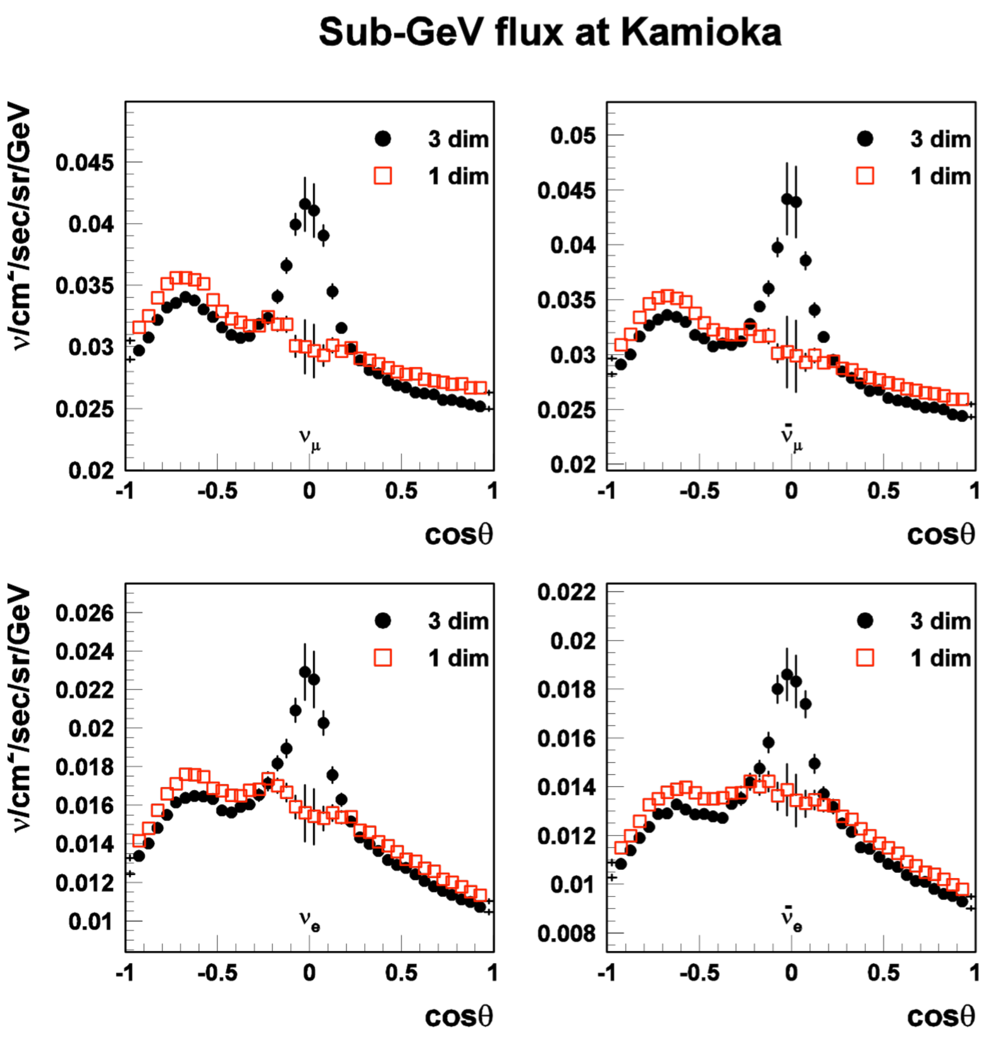
the same with spoiler



Magnetic field map used by FLUKA



FLUKA (3D) Calculation of Atmospheric ν Flux



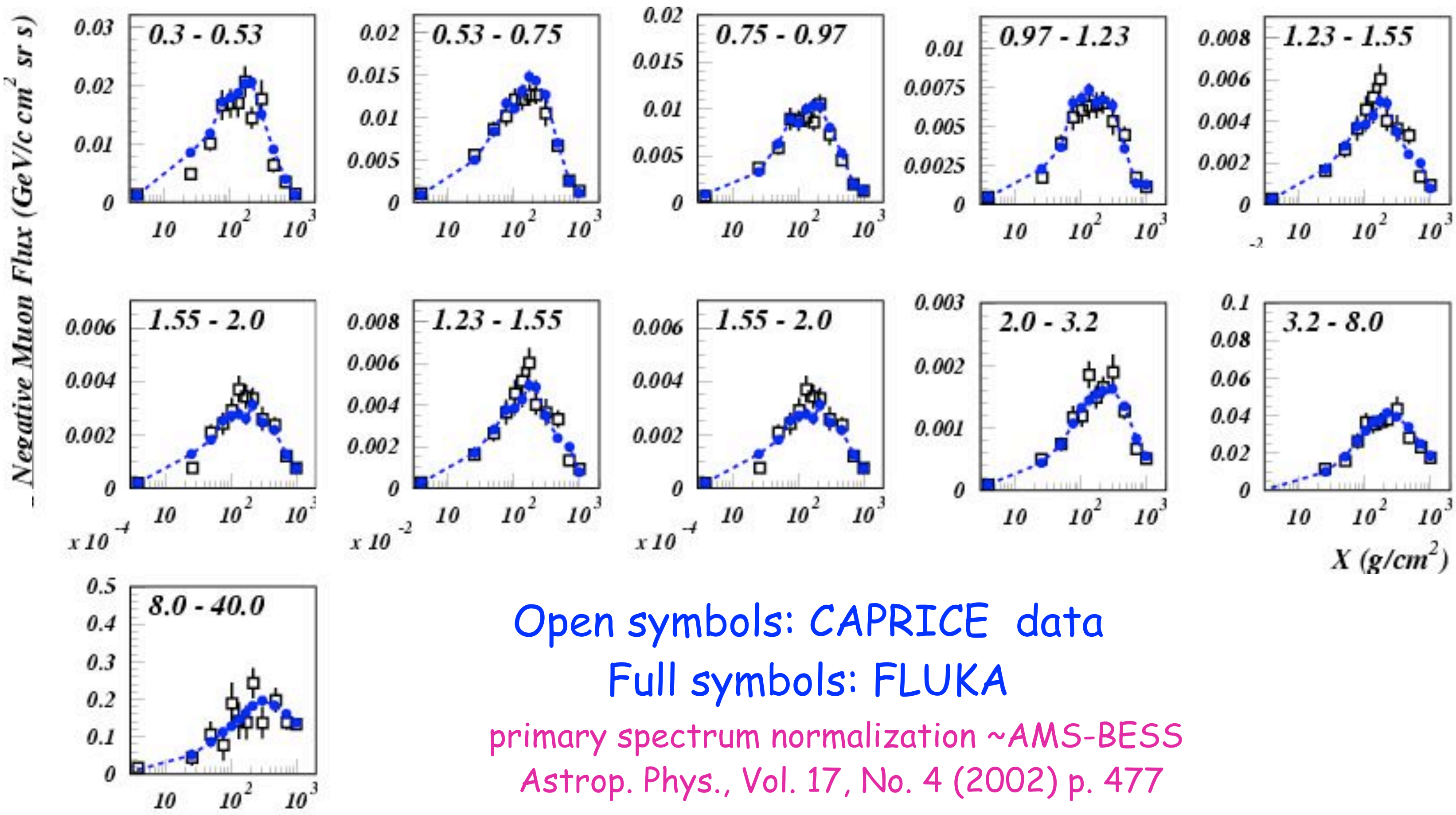
The first 3-D calculation of atmospheric neutrinos was done with FLUKA.

The enhancement in the horizontal direction, which cannot be predicted by a 1-D calculation, was fully unexpected, but is now generally acknowledged.

In the figure: angular distribution of ν_μ, $\bar{\nu}_{\mu}$, ν_e, $\bar{\nu}_e$.

In red: 1-D calculation

Negative muons at floating altitudes: CAPRICE94



Open symbols: CAPRICE data

Full symbols: FLUKA

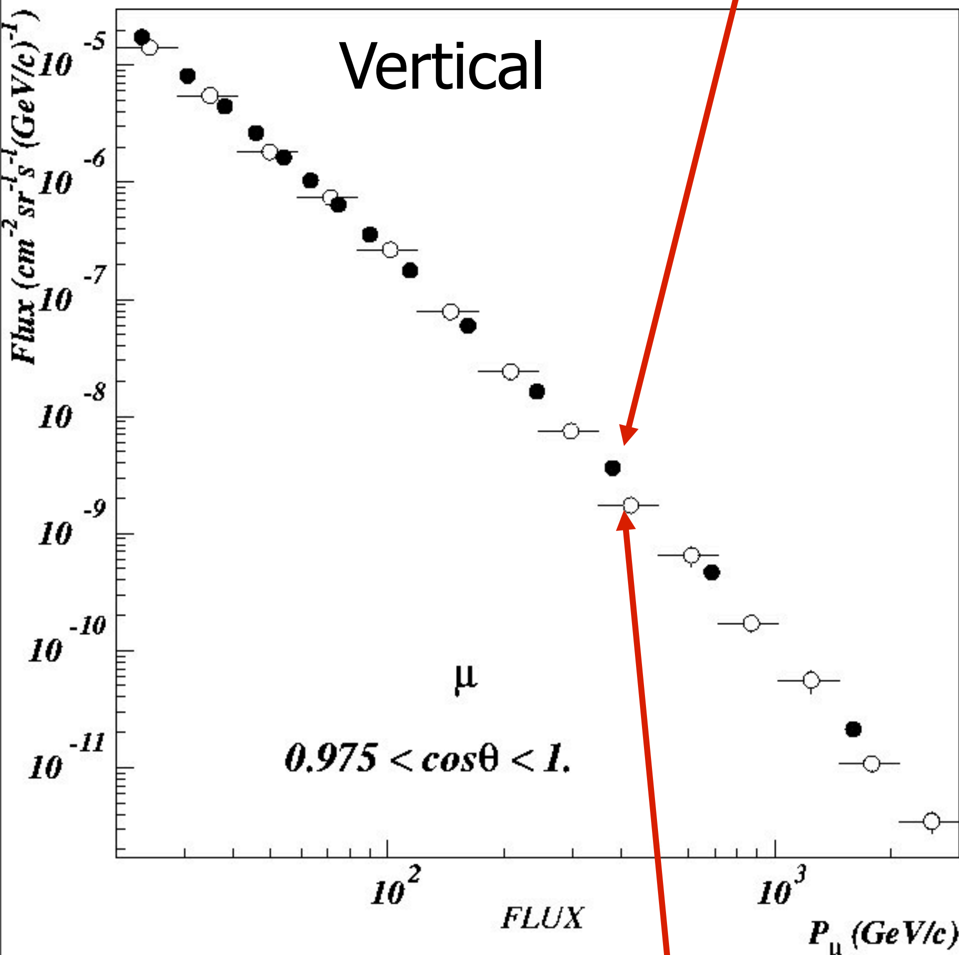
primary spectrum normalization ~AMS-BESS

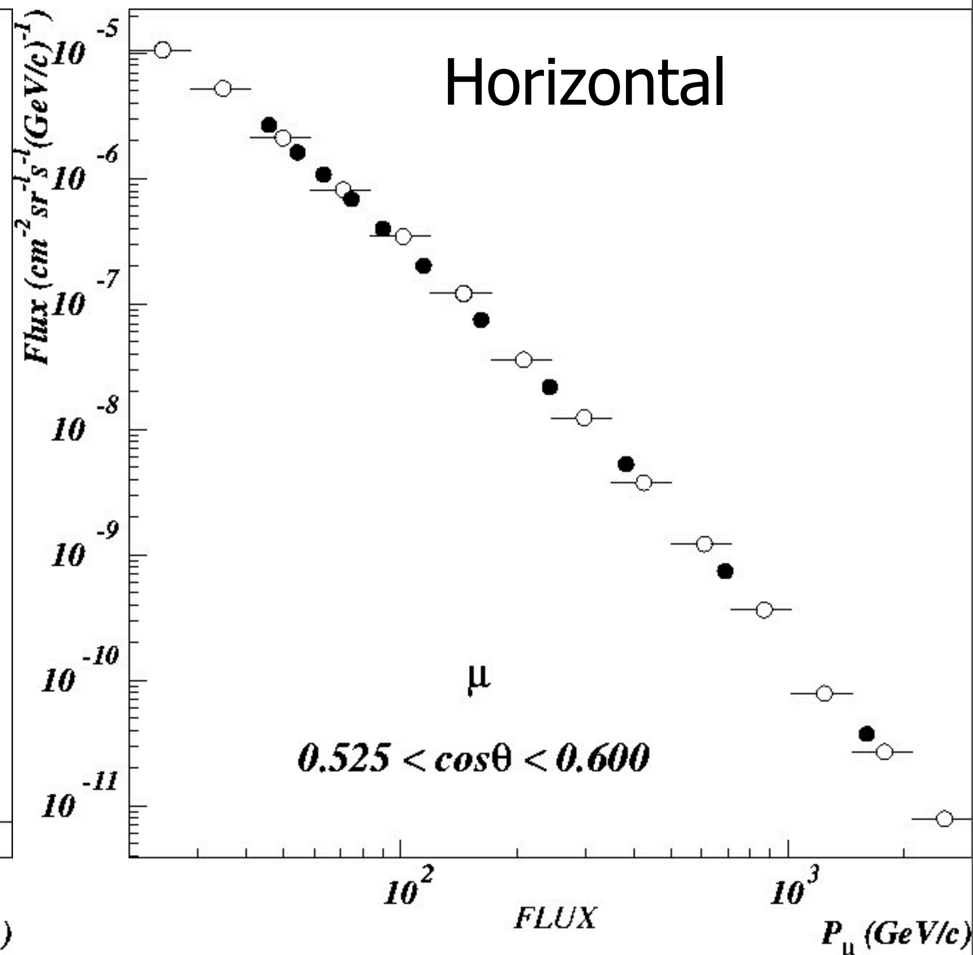
Astrop. Phys., Vol. 17, No. 4 (2002) p. 477

L3 Muons

(S.Muraro, PhD thesis Milano)

exp. data

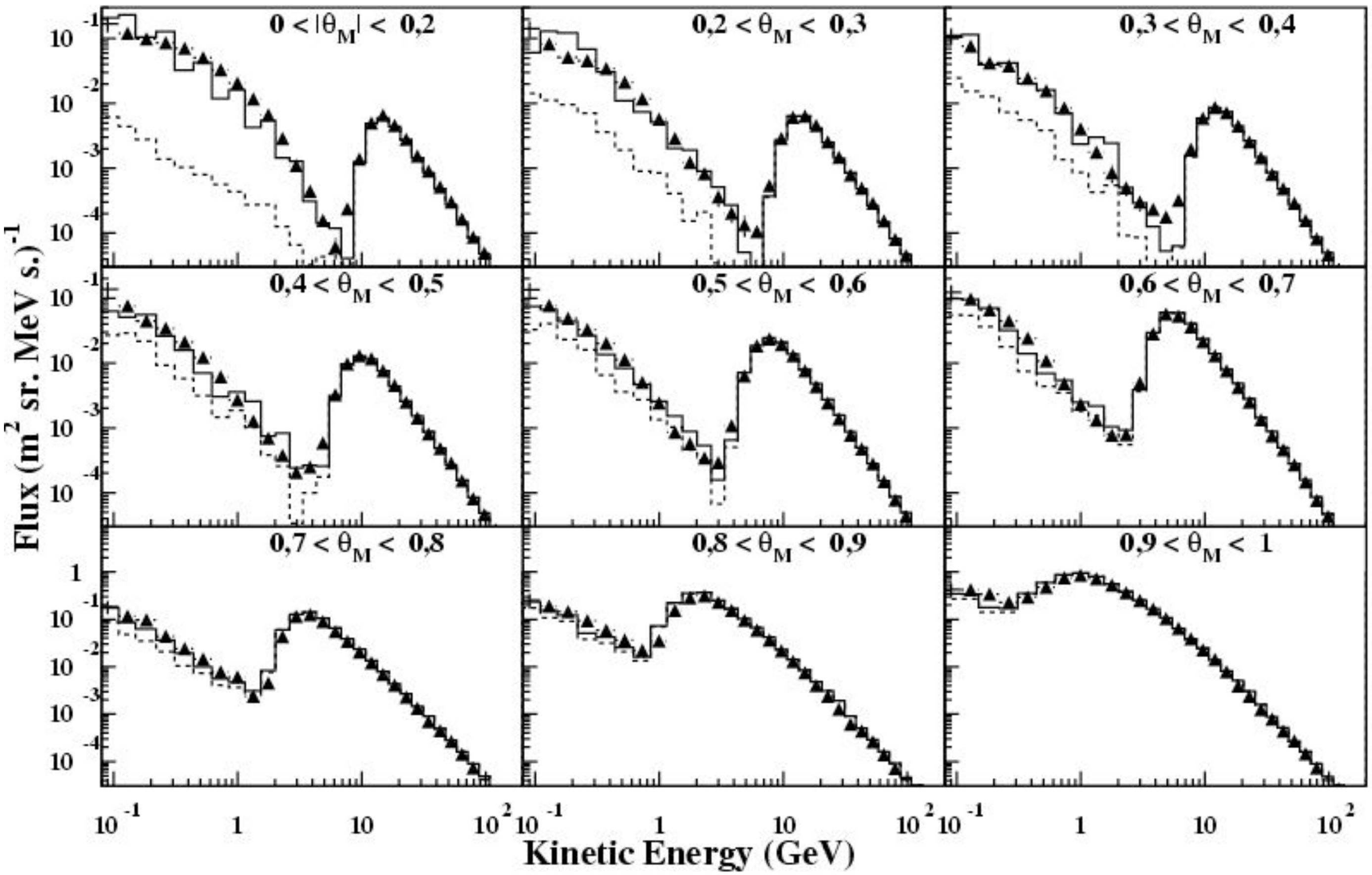




FLUKA simulation (absolute normalization!)

Reproduction of subcutoff structure of primary protons as detected by AMS

AMS near-earth orbit satellite experiment: downgoing proton flux



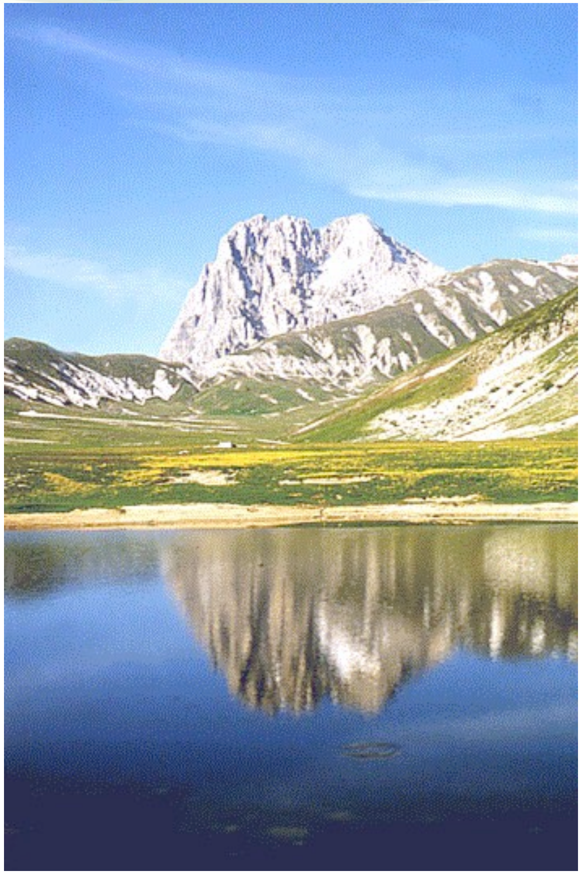
θ_M = geomagnetic latitude

Note the subcutoff component: secondary protons crossing the detector several times due to the geomagnetic field

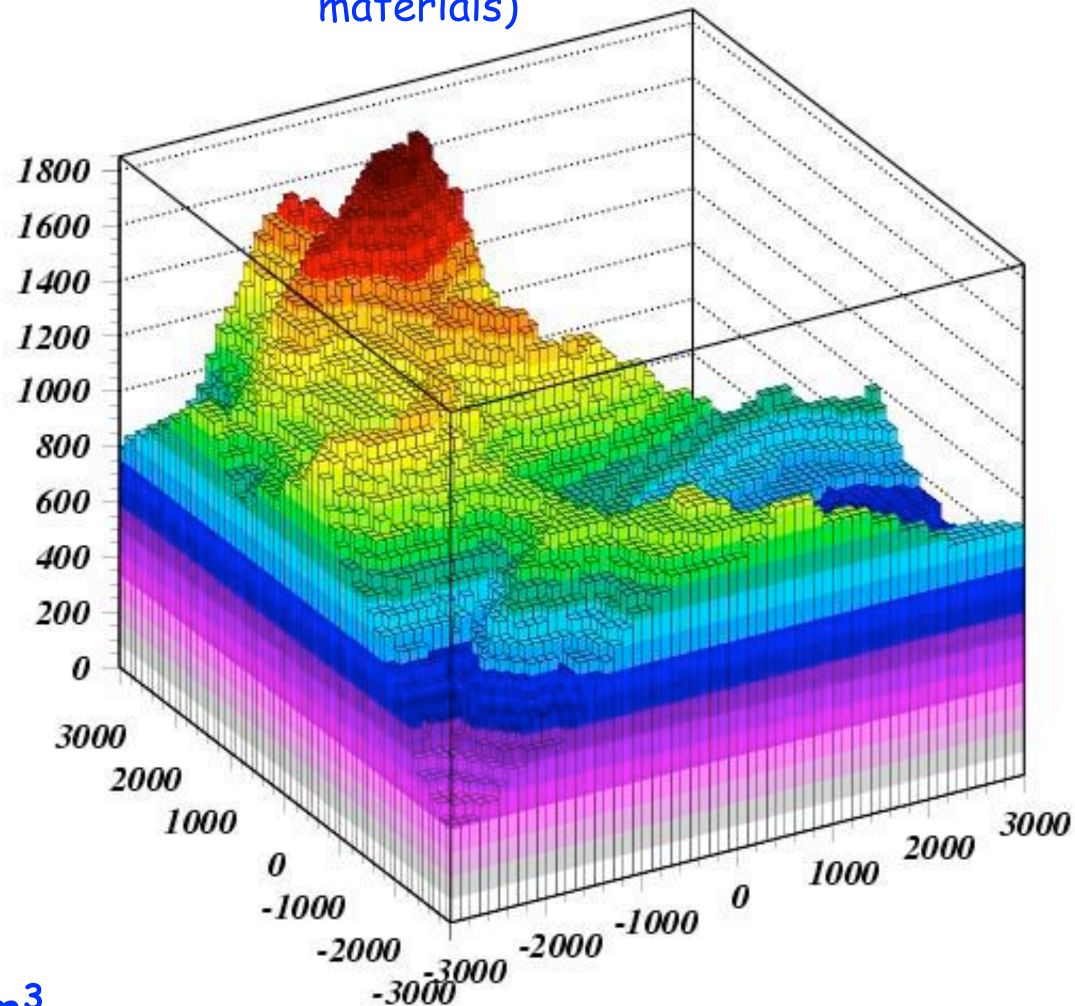
Simulation (solid line); AMS data (triangles); secondary protons counted once (dashed)

P. Zuccon et al., Int. J. Mod. Phys. A17, 1625 (2002)

Transport in Gran Sasso rock



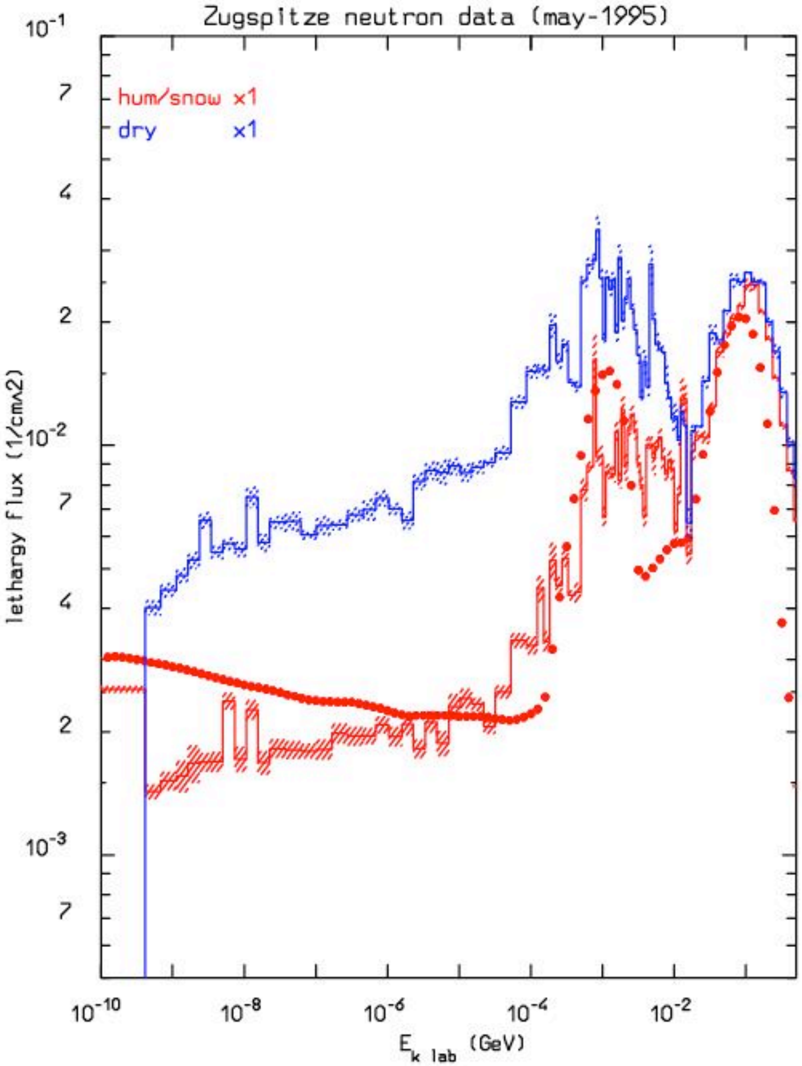
The layered geological structure has been reproduced (5 different materials)



Geometry of the mountain described using the FLUKA "voxel" system.

Here: 1 voxel = $100 \times 100 \times 50\ m^3$

Neutrons at 3000 m altitude



Neutron spectra on the Zugspitze (2963 m)

Red points: experimental data

Blue histogram:

FLUKA calculation (dry conditions)

Red histogram:

FLUKA calculation (wet conditions and snow on the ground)

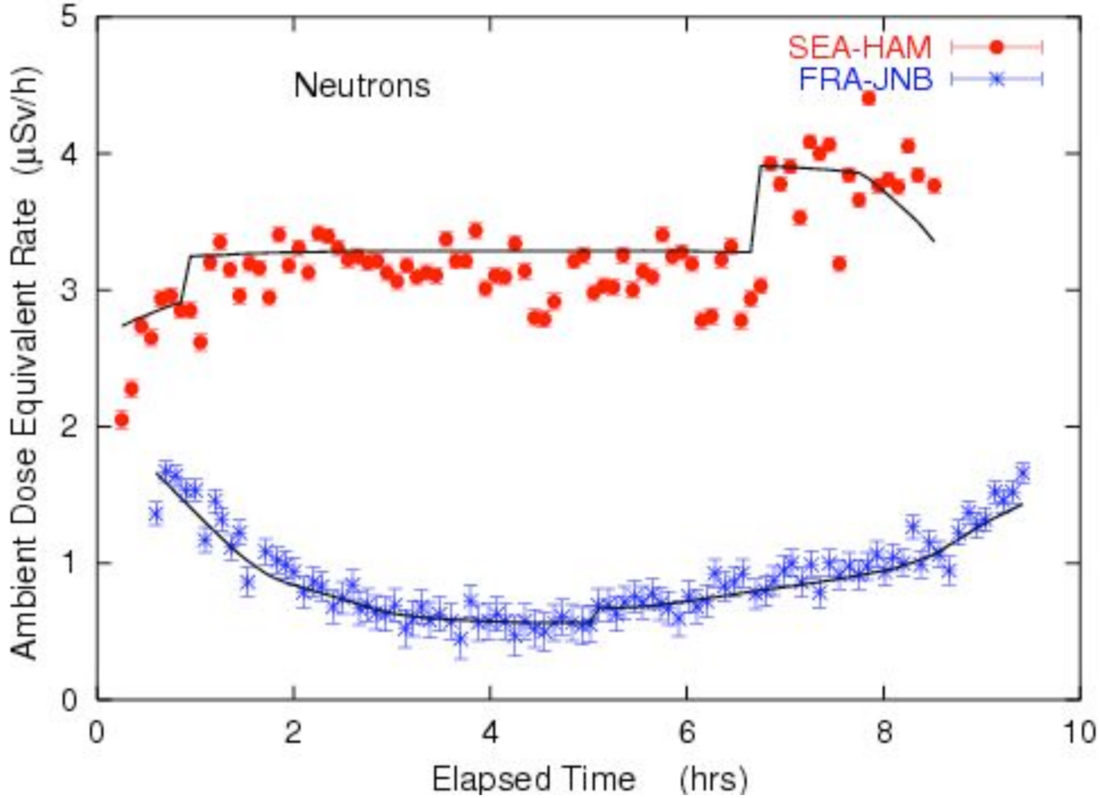
H. Schraube et al., Rad. Prot. Dosim. 70, 405 (1997),

Rad. Prot. Dosim. 86, 309 (1999)

S. Roesler et al., Adv. Space Res. 21, 1717 (1998)

Aircrew doses

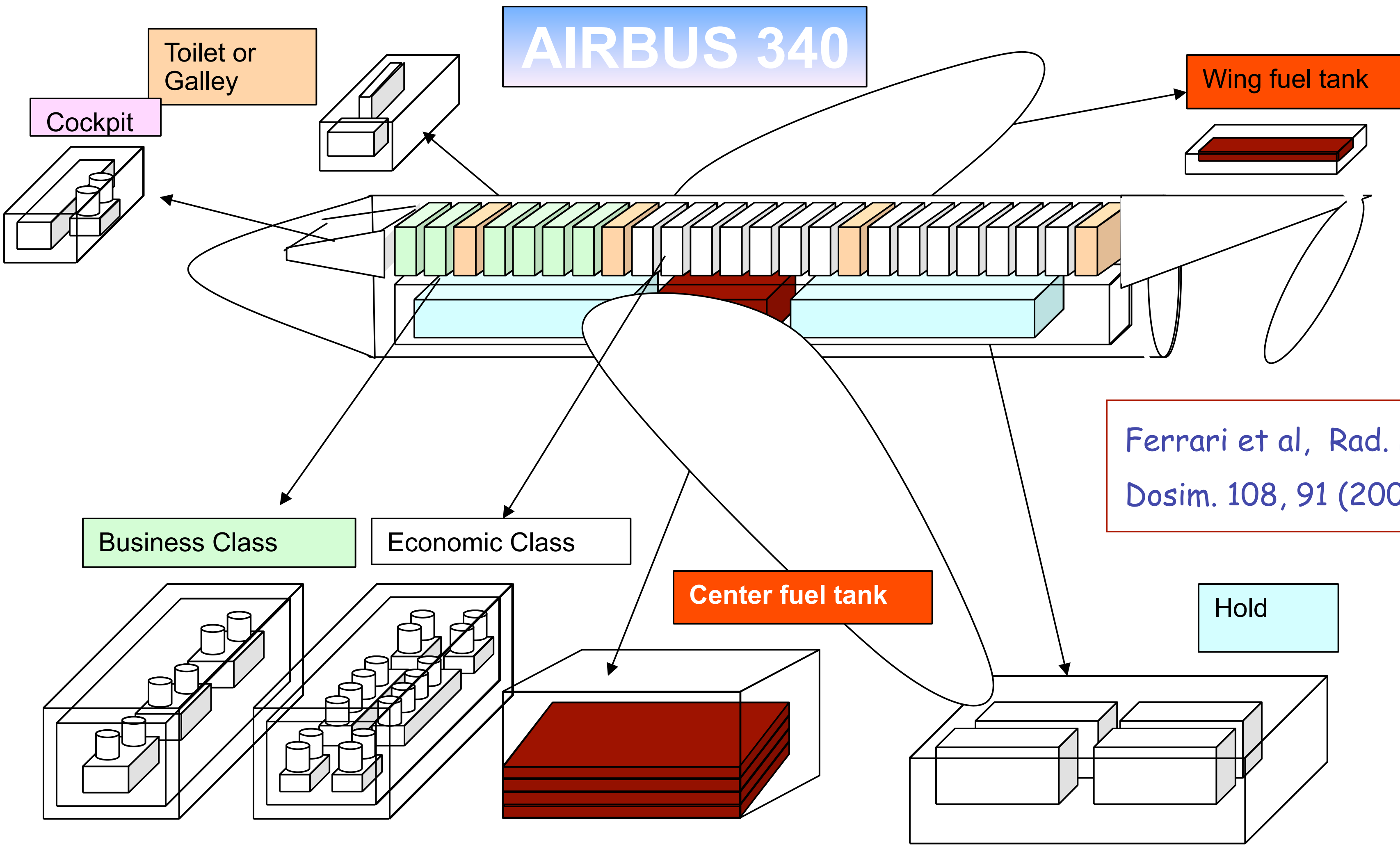
Roesler et al.,
Rad. Prot. Dosim.
98, 367 (2002)



Ambient dose equivalent from neutrons at solar maximum on commercial flights from Seattle to Hamburg and from Frankfurt to Johannesburg.

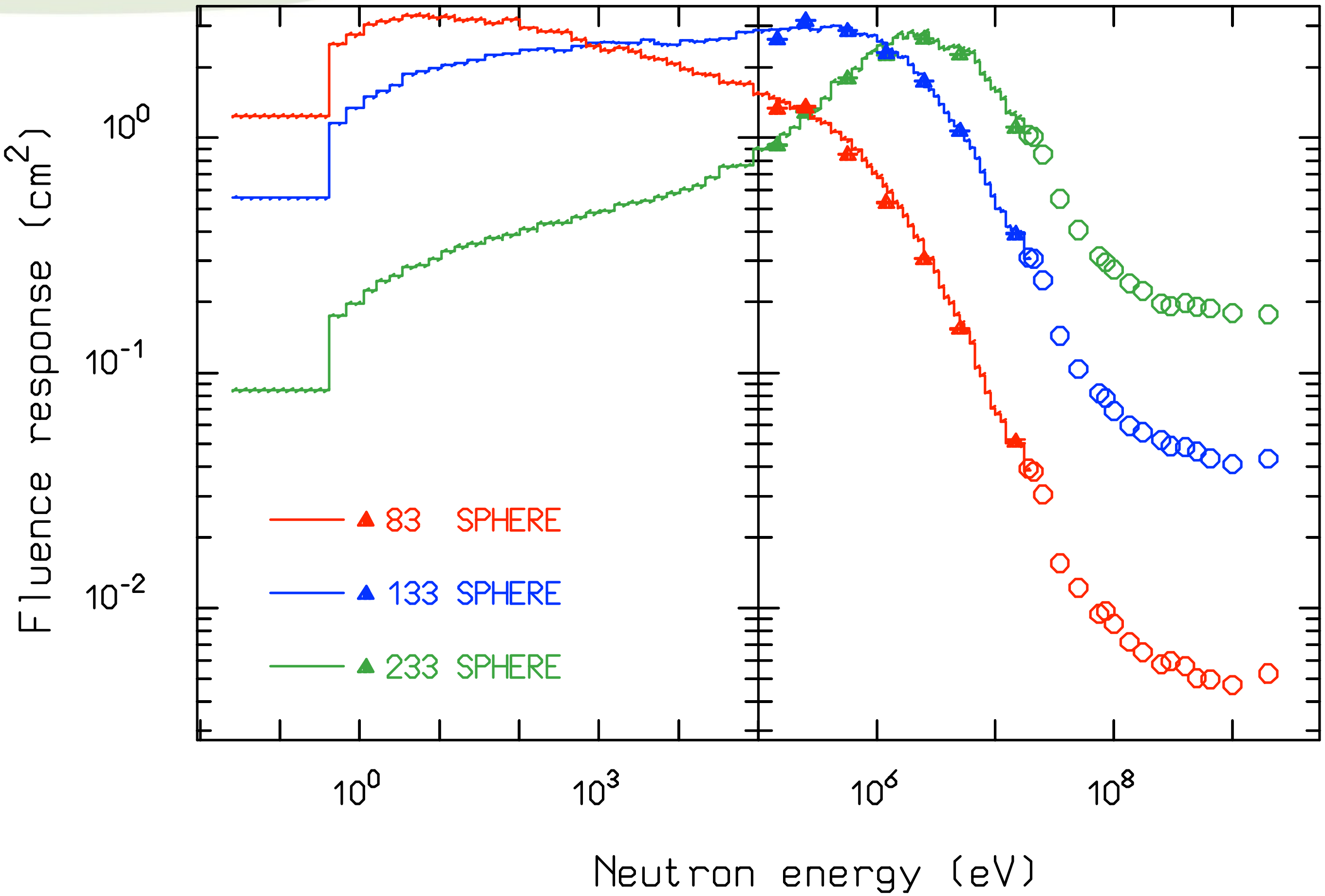
Solid lines: FLUKA simulation

Dosimetry applications: doses to aircrew and passengers



Ferrari et al, Rad. Prot. Dosim. 108, 91 (2004)

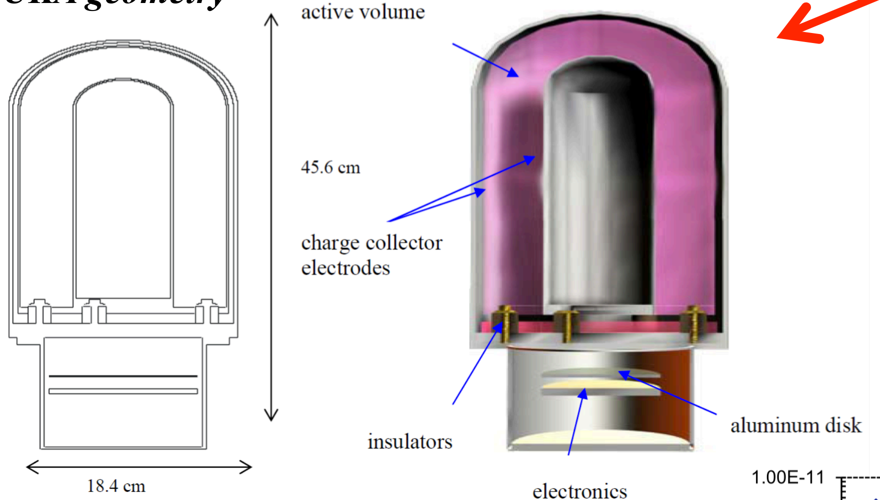
Instrument calibration (PTB)



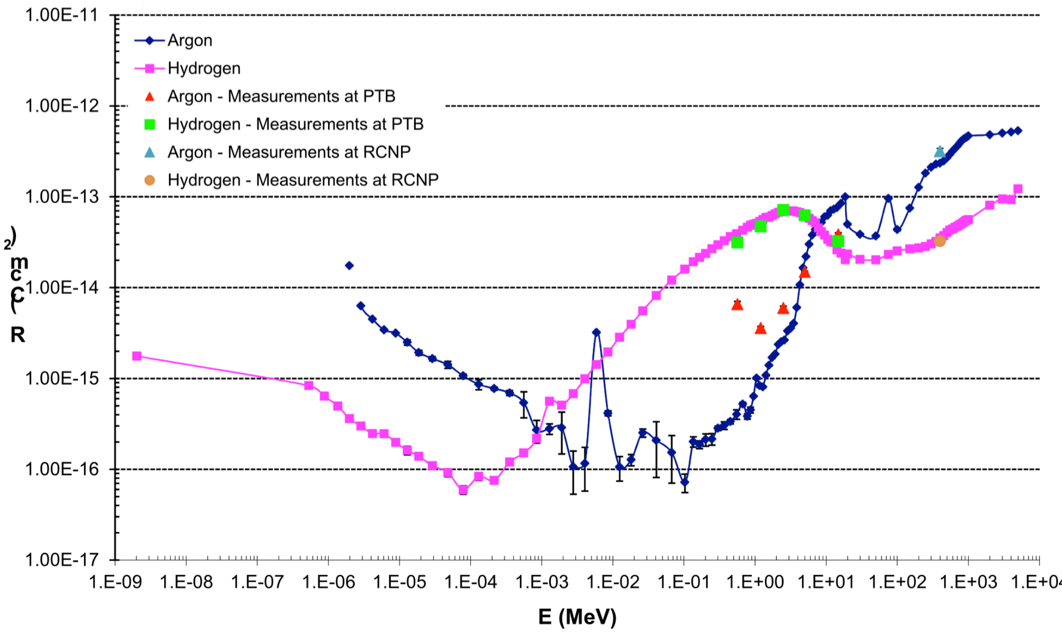
Calibration of three different Bonner spheres (with ^{3}He counters) with monoenergetic neutron beams at PTB (full symbols), compared with simulation (dashed histograms and open symbols)

Radiation detector responses

FLUKA geometry



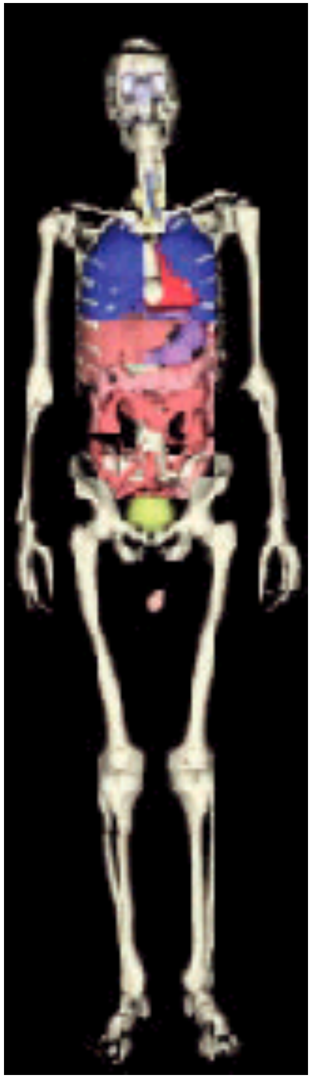
- IG5 (Centronics) high-pressure ionization chambers (5.2 l, 20 bar)
- hydrogen or argon gas filling
- monitor of prompt radiation fields in areas occupied by personnel
- response measurements and simulations in mono-energetic neutron fields (PTB, RCNP Osaka)



© C.Theis *et al.*, CERN-SC-2004-023-RP-TN
H. Vincke *et al.*, *Response of ionization chambers to high-energy mono-energetic neutrons*, Nuclear Technology, Volume 168 – 1, 2009

The voxel geometry

- FLUKA can embed voxel structures within its standard combinatorial geometry
- Transport through the voxels is optimized and efficient
- Raw CT-scan outputs can be imported



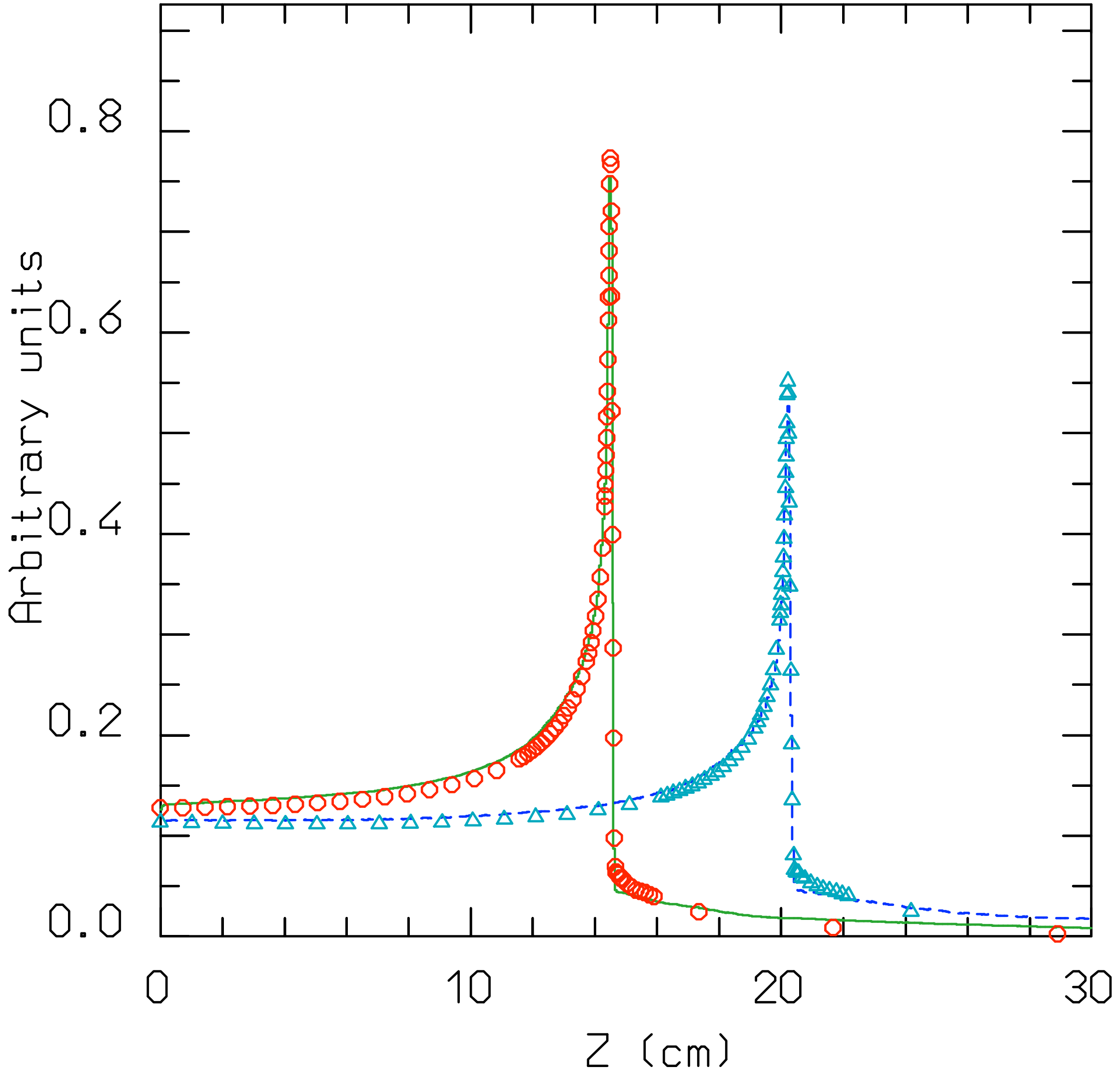
The GOLEM phantom
Petoussi-Henss et al, 2002

Bragg peaks vs exp. data: ^{12}C @ 270 & 330 MeV/n

Dose vs depth distribution for 270 and 330 MeV/n ^{12}C ions on a water phantom.

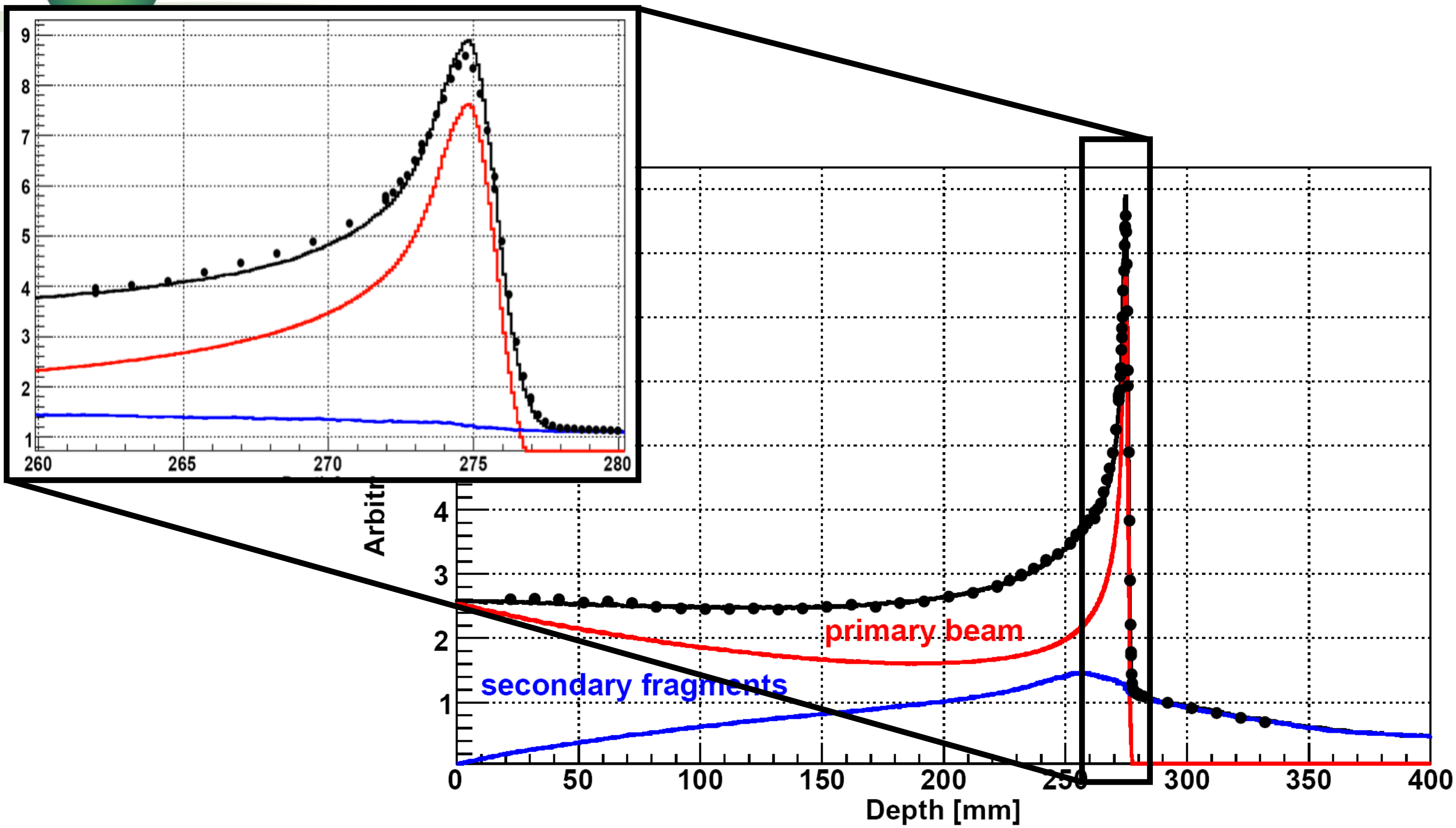
The full green and dashed blue lines are the FLUKA predictions

The symbols are exp data from GSI



Exp. Data Jpn.J.Med.Phys. <u>18</u>, 1,1998

^{12}C @ 400 MeV/n on water: Bragg peak

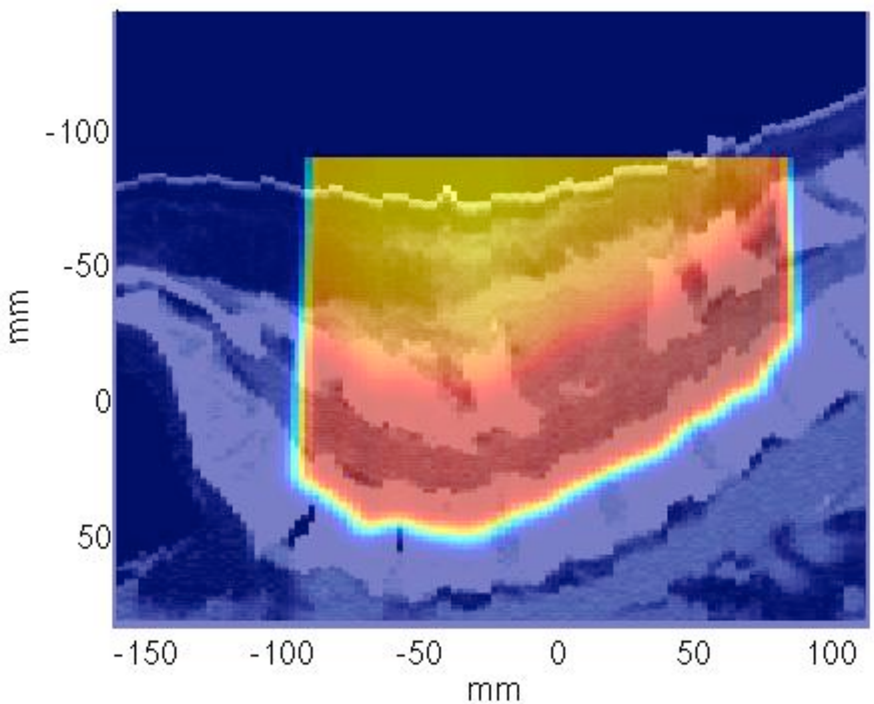


Beam energy spread: 0.2 MeV/n FWHM

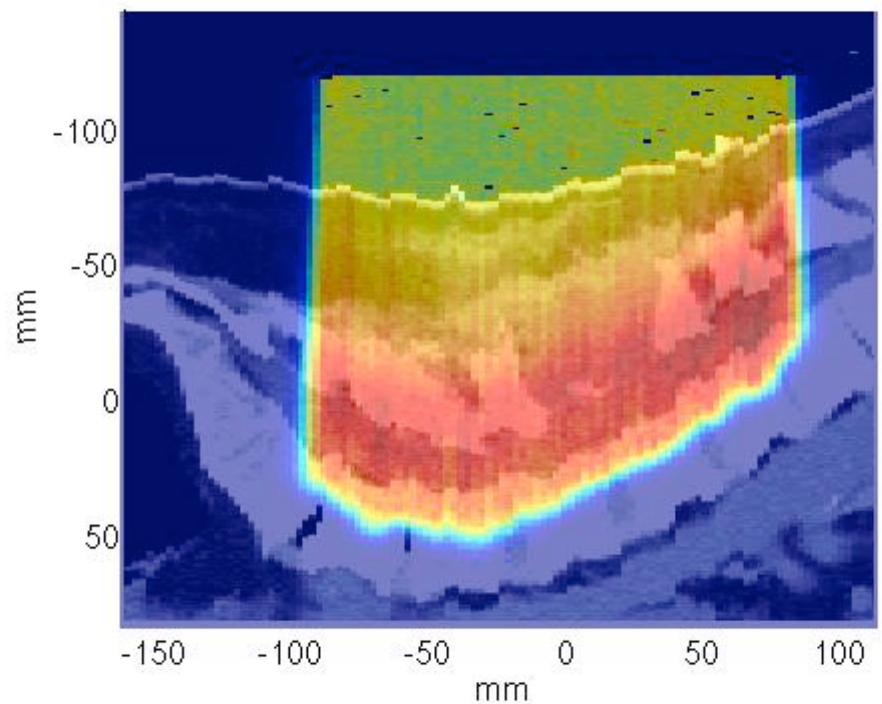
Preliminary exp. data courtesy of E.Haettner (Diploma thesis), D.Schardt, GSI, and S.Brons, K.Parodi, HIT. MC simulations: A.Mairani PhD thesis, Pavia

Proton therapy: A Real Case at MGH*

Treatment planning system



FLUKA simulation



Planned dose distribution in a patient with a spinal tumor

* K. Parodi, H. Paganetti and T. Bortfeld, **M**assachusetts **G**eneral **H**ospital

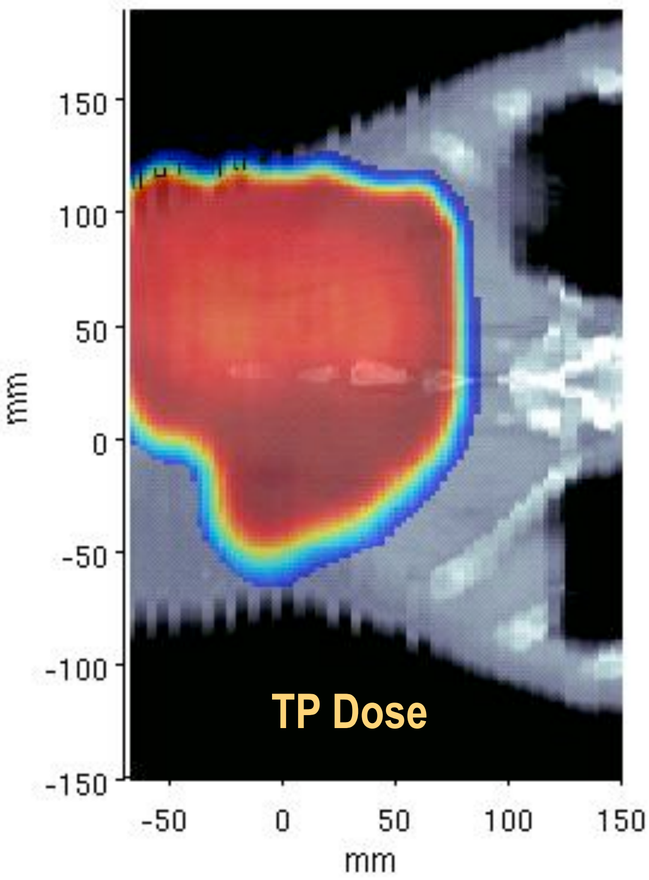
Spine

L-spine chordoma, 1.8 Gy, ΔT ~ 17 min

K. Parodi et al.

Spine

L-spine chordoma, 1.8 Gy, ΔT ~ 17 min



K. Parodi et al.

Spine

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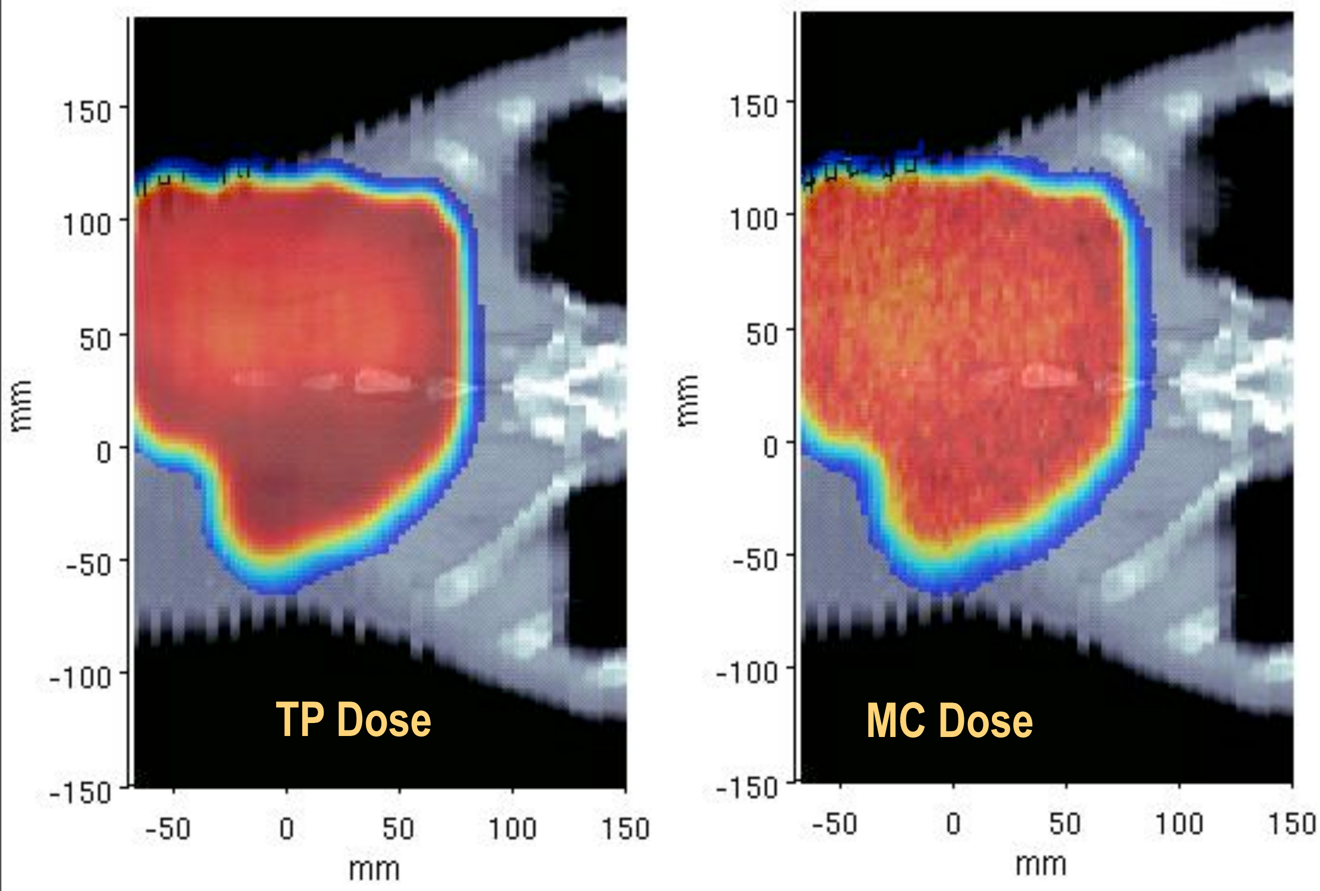

K. Parodi et al.

Spine

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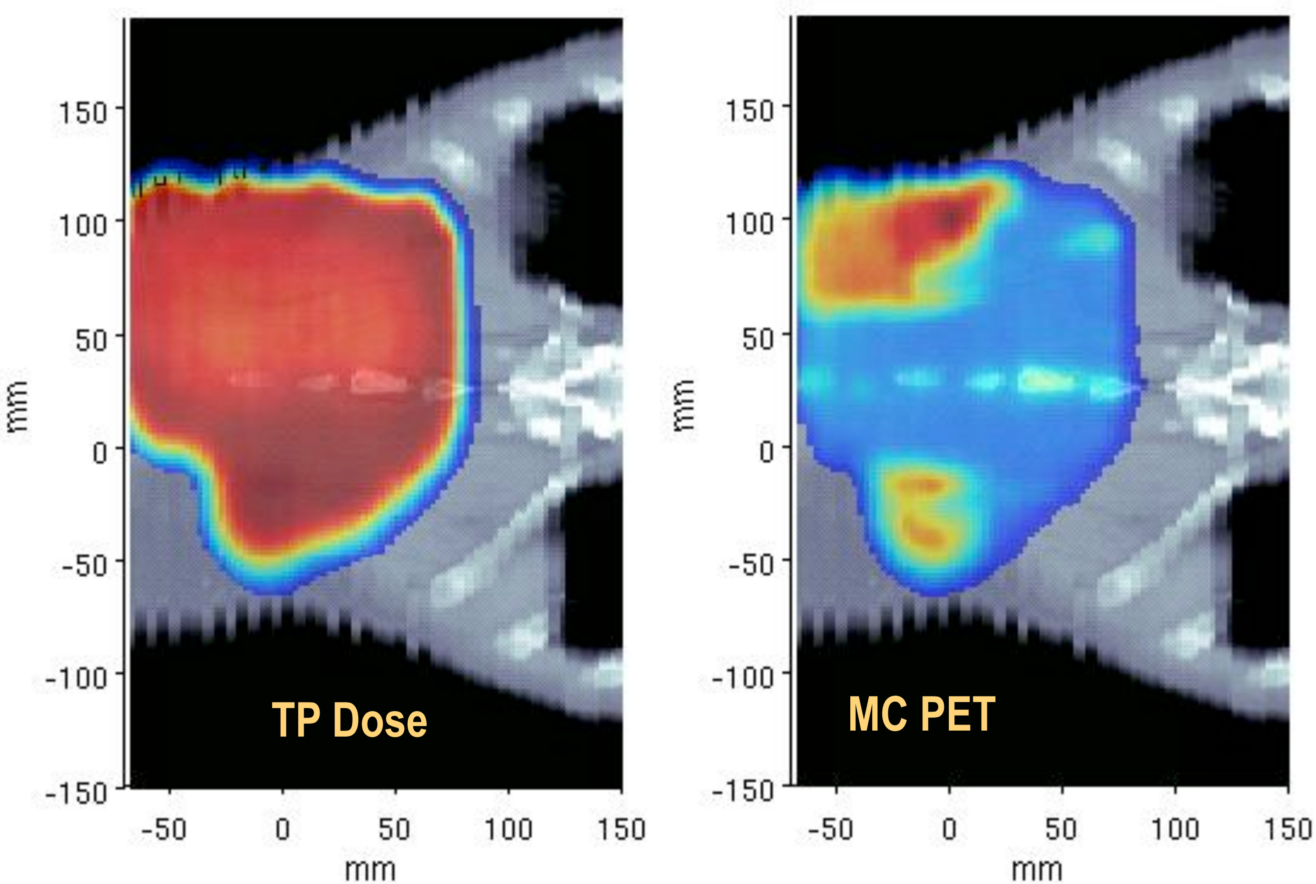
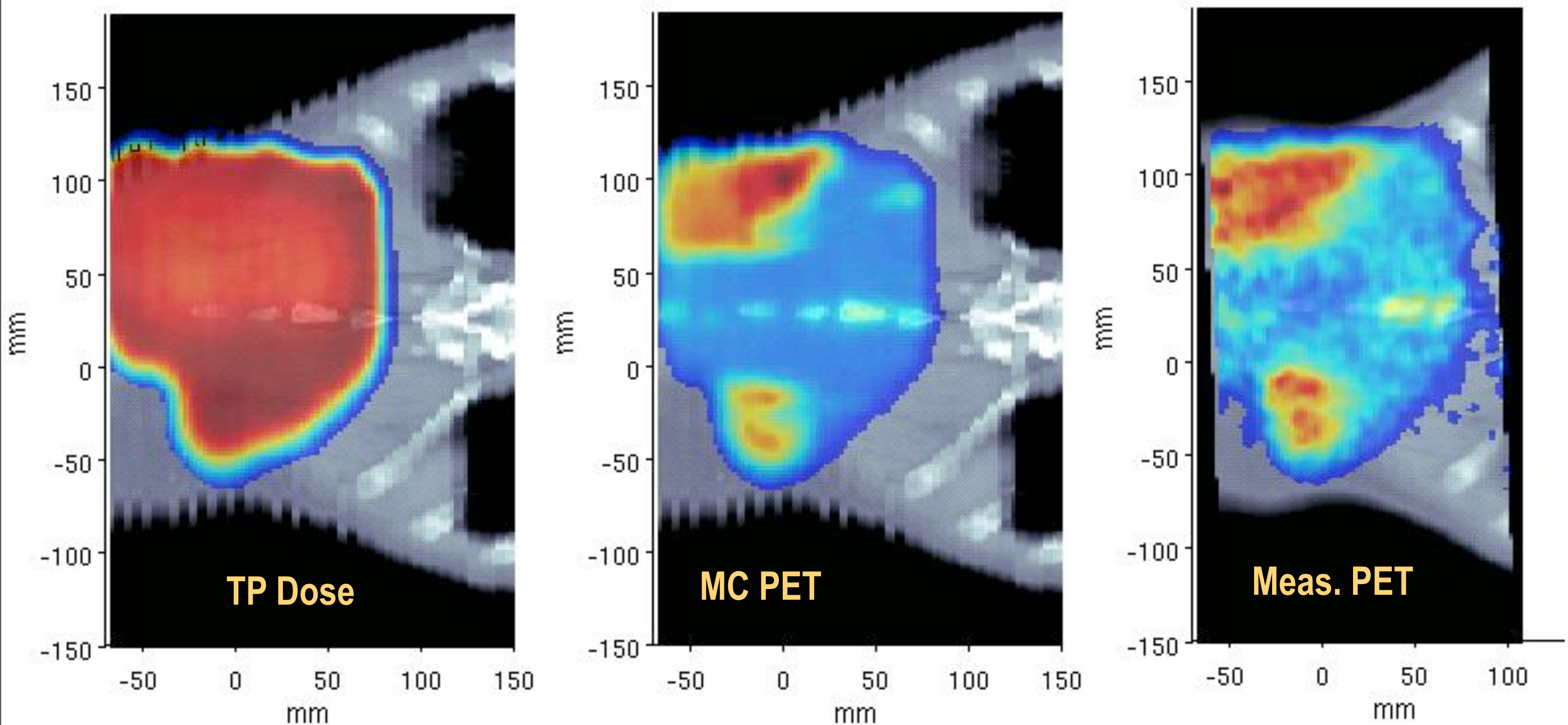


K. Parodi et al.

Spine

L-spine chordoma, 1.8 Gy, ΔT ~ 17 min

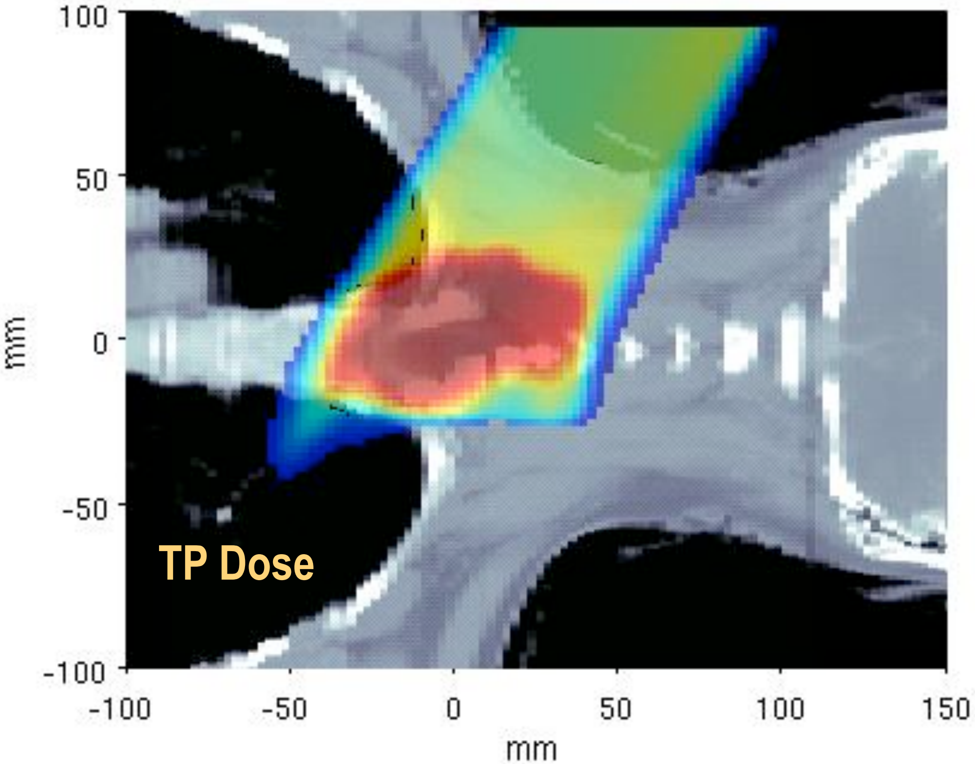


K. Parodi et al.

Hadron therapy: Spine

T-spine Chondrosarcoma

K. Parodi et al.



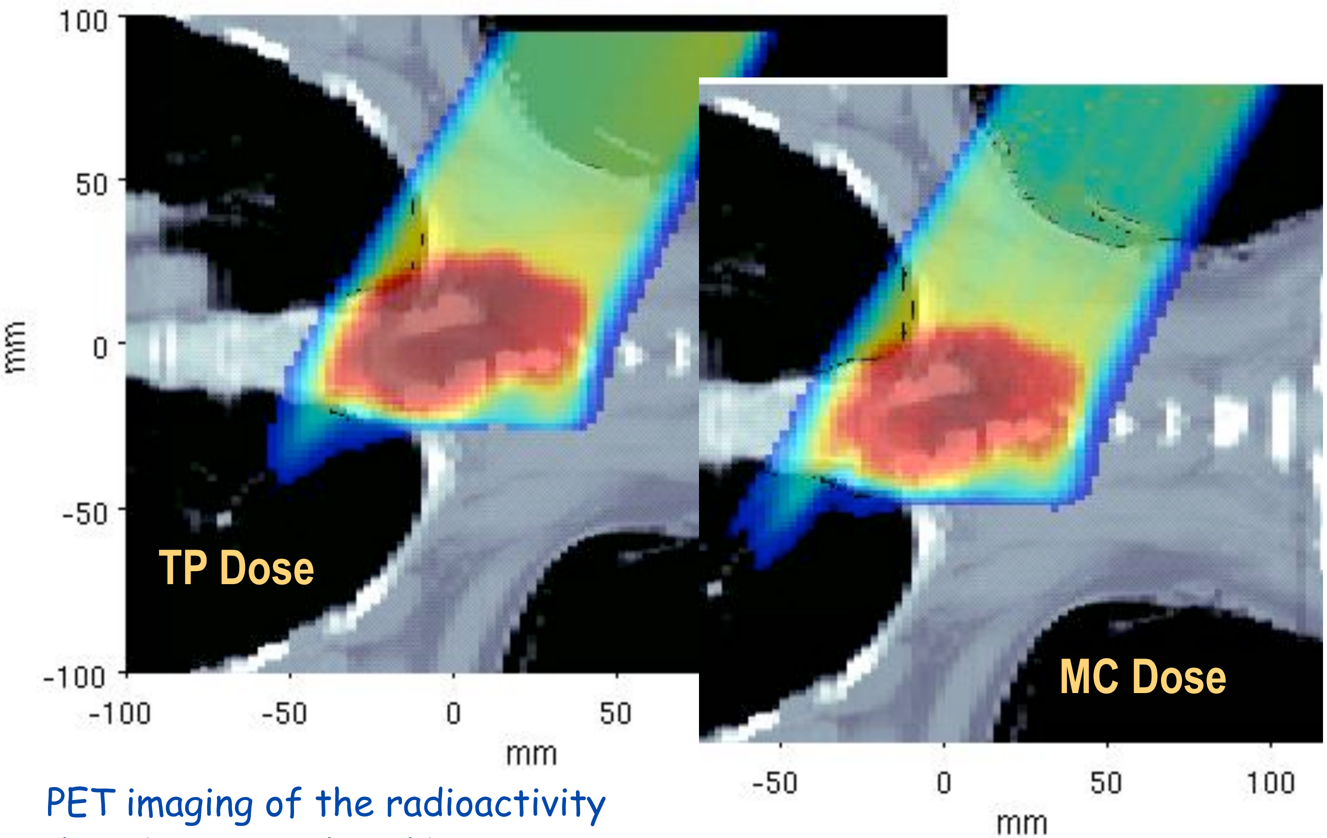
Spatial correlation between activity and dose profile provides information about particle range, dose localization and stability of the treatment

PET imaging of the radioactivity distributions induced by therapeutic irradiation is the only feasible method for an in vivo and non-invasive monitoring of radiation treatments with ion beams.

Hadron therapy: Spine

T-spine Chondrosarcoma

K. Parodi et al.



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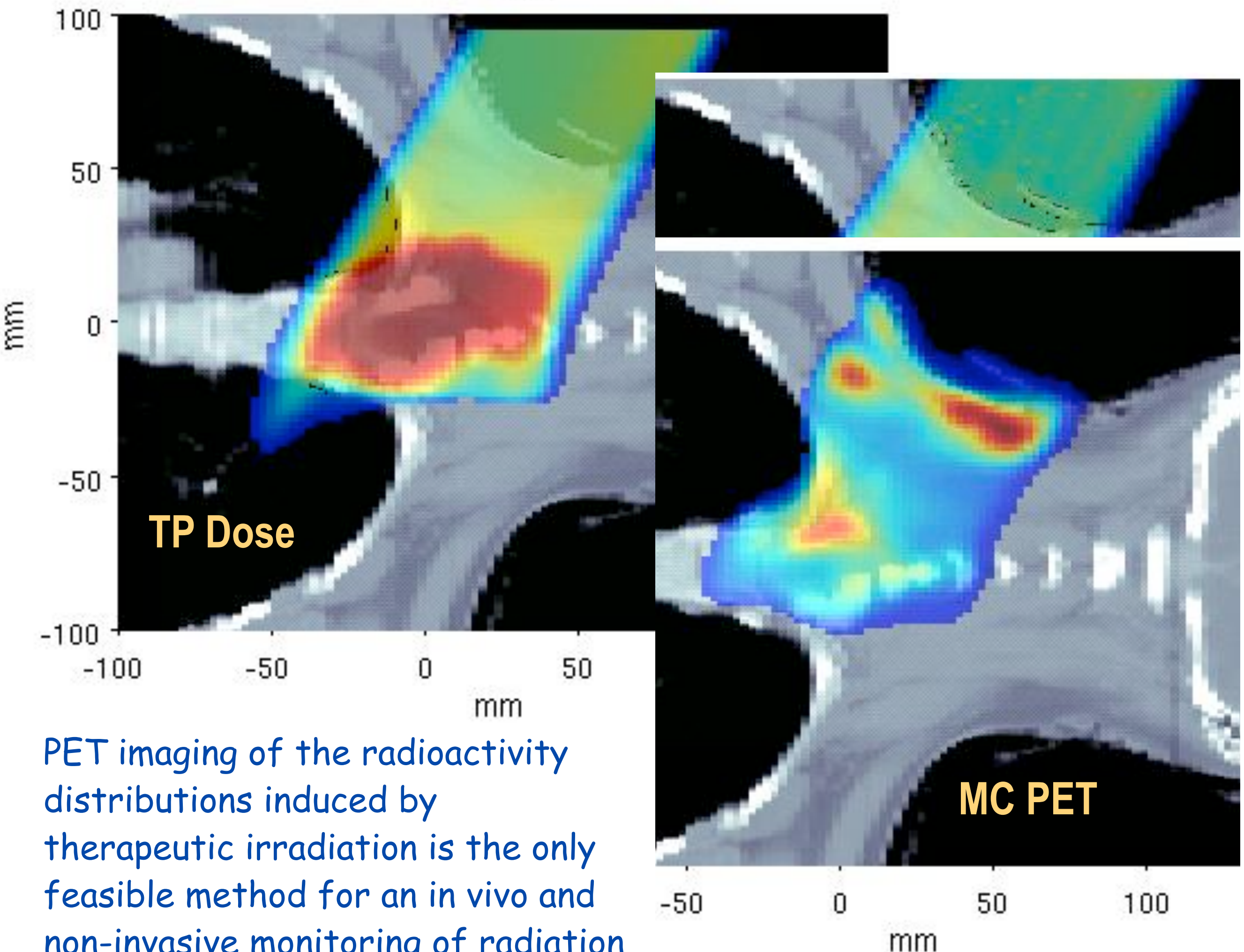

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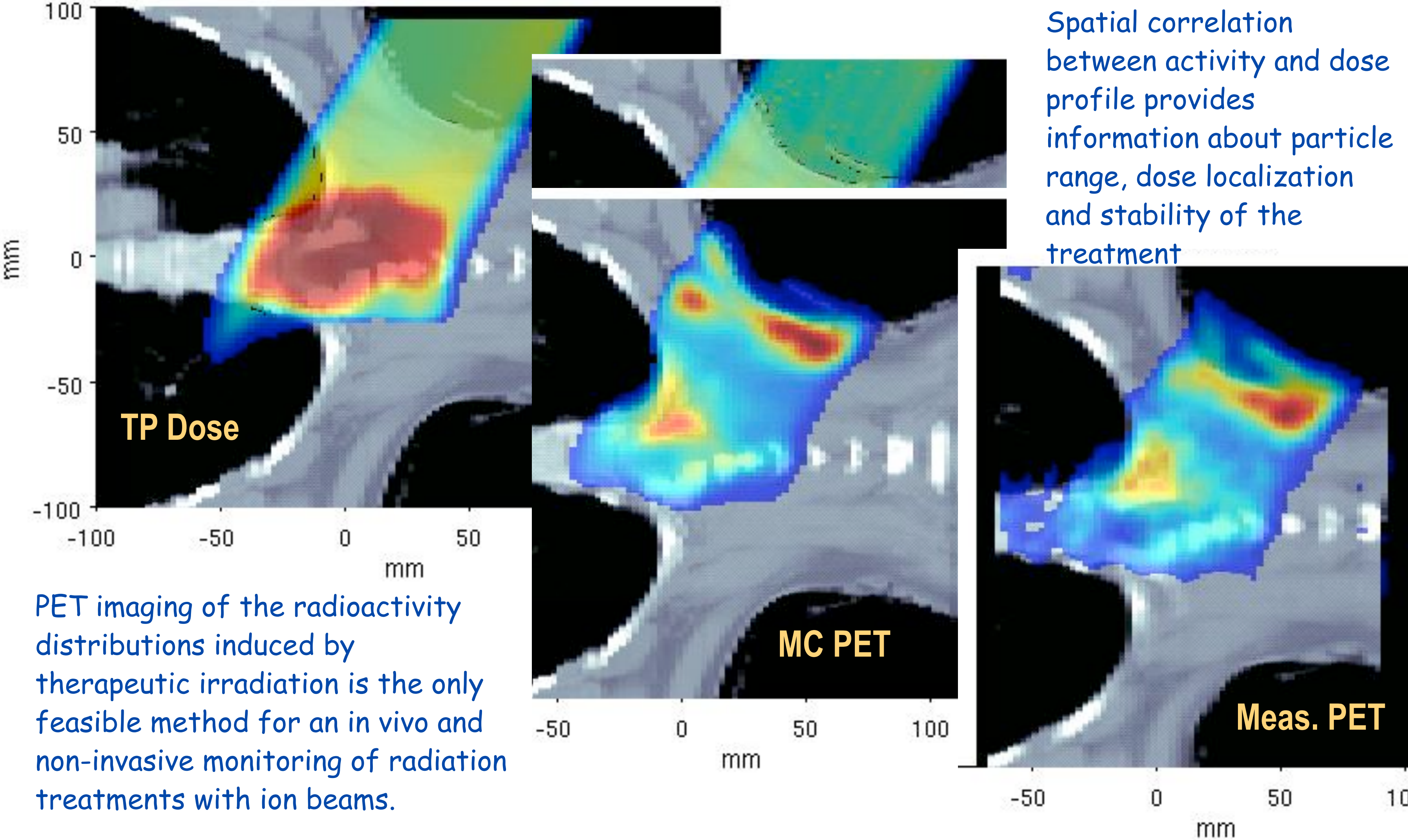
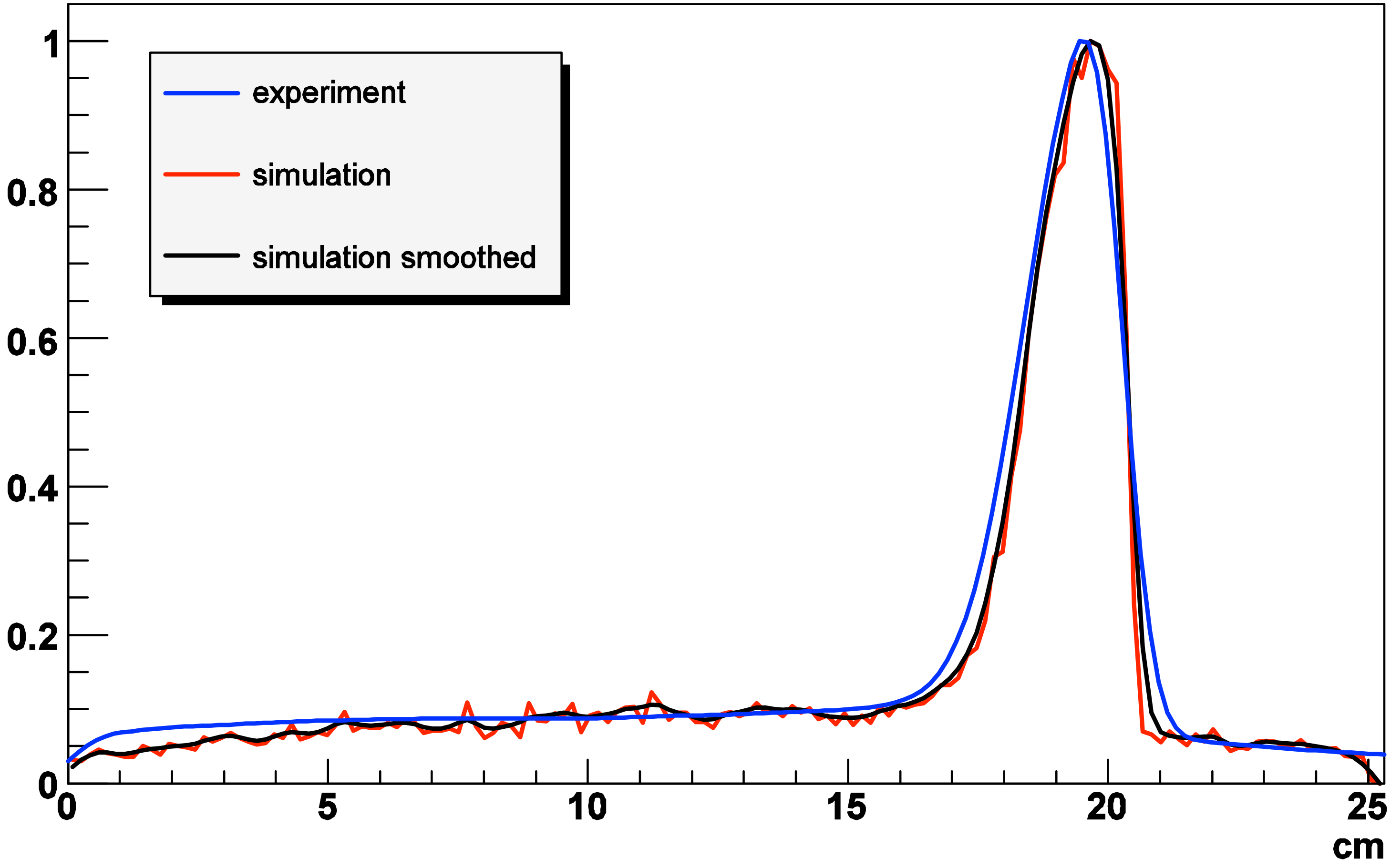


PET imaging of the radioactivity distributions induced by therapeutic irradiation is the only feasible method for an in vivo and non-invasive monitoring of radiation treatments with ion beams.

Example with RQMD AND BME

337 Mev/u ^{12}C on water, after irradiation

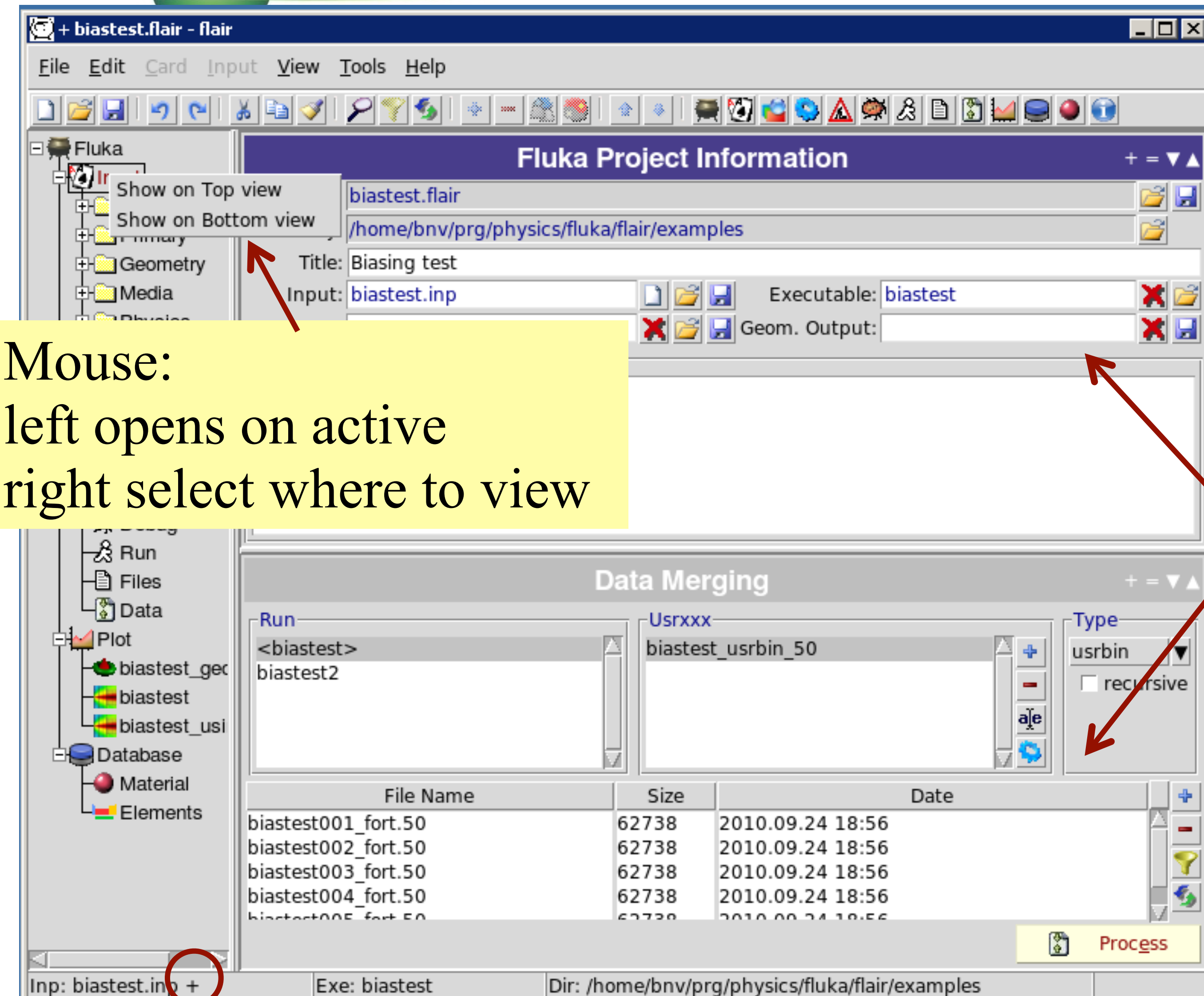
longitudinal distribution of β+ emitters



FLUKA


Flair
File Edit Card Input Plot View Options Help
Fluka
Input
General
Primary
Geometry
Media
Physics
Transport
Biasing
Scoring
Usrbin
Unit 50
Particle ENERGY
Score
Developers
Preprocessor
TITLE Heavy Ion Pair production test
GLOBAL
DEFAULTS
BEAM
BEAMPOS
HI-PROPE
EVENTYPE
#if
DPMJET
#endif
GEOBEGIN
SPH
SPH
RPP COIL
Preprocessor: variable definition
#define DPMJET
Inp: hvpair.inp
Exe: hvfluka

Interface



Mouse:
left opens on active
right select where to view

active

+ vertical/horizontal
= equalize
▼ minimize
▲ maximize

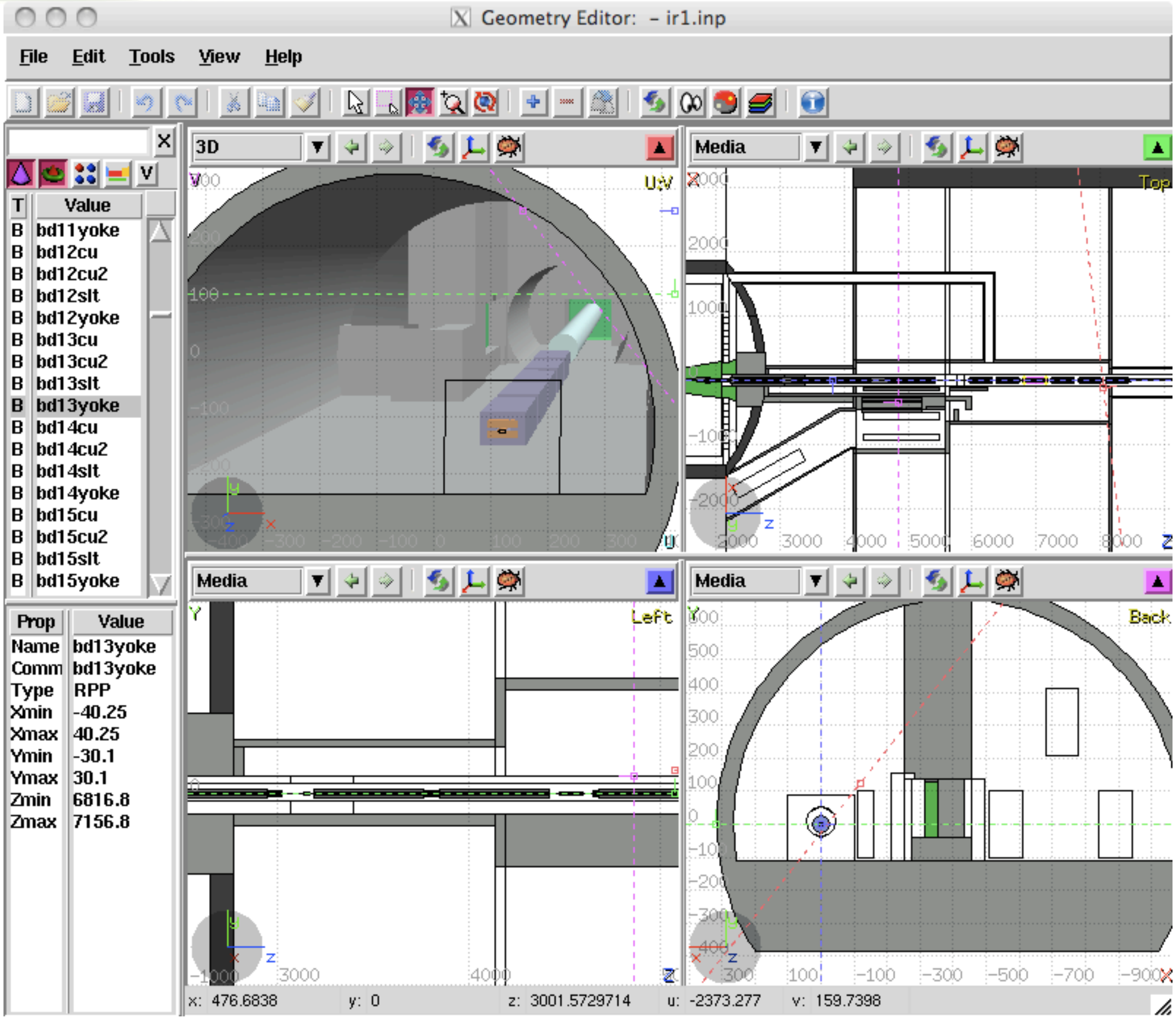
2 working frames

inactive

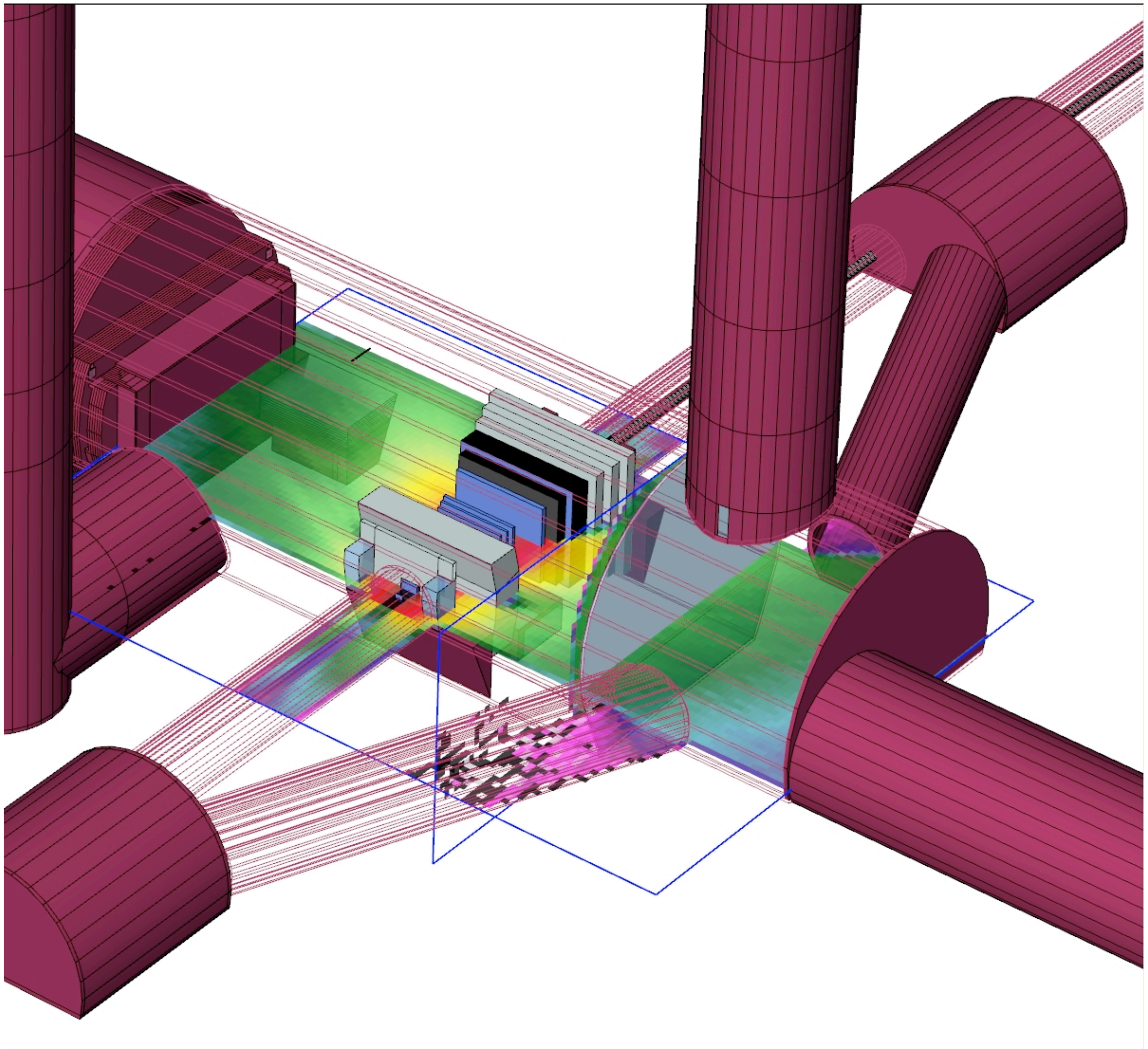
click to activate

input modified and not saved

Geometry Editor: Interface



SimpleGeo



END

History

The early days

The beginning: 1962: Johannes Ranft (Leipzig) and Hans Geibel (CERN): Monte Carlo for high-energy proton beams

The name: 1970: study of event-by-event fluctuations in a NaI calorimeter (FLUktuierende KAskade)

Early 70's to ≈1987: J. Ranft and coworkers (Leipzig University) with contributions from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò)

Link with EGS4 in 1986, later abandoned

History

The modern code: some dates

Since 1989: mostly INFN Milan (A. Ferrari, P.R. Sala): little or no remnants of older versions. Link with the past: J. Ranft and A. Fassò

1990: LAHET / MCNPX: high-energy hadronic FLUKA generator

No further update

1993: G-FLUKA (the FLUKA hadronic package interfaced with GEANT3). *No further update*

1998: FLUGG, interface to GEANT4 geometry

2000: grant from NASA to develop heavy ion interactions and transport

2001: the INFN FLUKA Project

2003: official CERN-INFN collaboration to develop, maintain and distribute FLUKA

2004: FLUKA hadron event generator interfaced to CORSIKA

Inelastic hN interactions

Intermediate Energies

- $N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV

  important above 700 MeV

  $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV
- Dominance of the $\Delta(1232)$ resonance and of the N* resonances → reactions treated in the framework of the isobar model → all reactions proceed through an intermediate state containing at least one resonance
- Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible

High Energies: Dual Parton Model

- Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework
- each of the two hadrons splits into 2 colored partons → combination into 2 colourless chains → 2 back-to-back jets
- each jet is then hadronized into physical hadrons

Generalized Intra-Nuclear Cascade: the PEANUT model

Main assets of the full GINC as implemented in FLUKA below 5 GeV:

- Nucleus divided into 16 radial zones of different density, plus 6 outside the nucleus to account for nuclear potential, plus 10 for charged particles
- Different nuclear densities for neutrons and protons
- Nuclear (complex) optical potential → curved trajectories in the mean nuclear+Coulomb field (reflection, refraction)
- Updating binding energy (from mass tables) after each particle emission
- Multibody absorption for $\pi^{+/0/-}$ $K^{-/0}$, μ^-
- Energy-momentum conservation including the recoil of the residual nucleus
- Nucleon Fermi motion including wave packet-like uncertainty smearing
- Quantum effects (mostly suppressive): Pauli blocking, Formation zone, Nucleon antisymmetrization, Nucleon-nucleon hard-core correlations, Coherence length

Preequilibrium in FLUKA

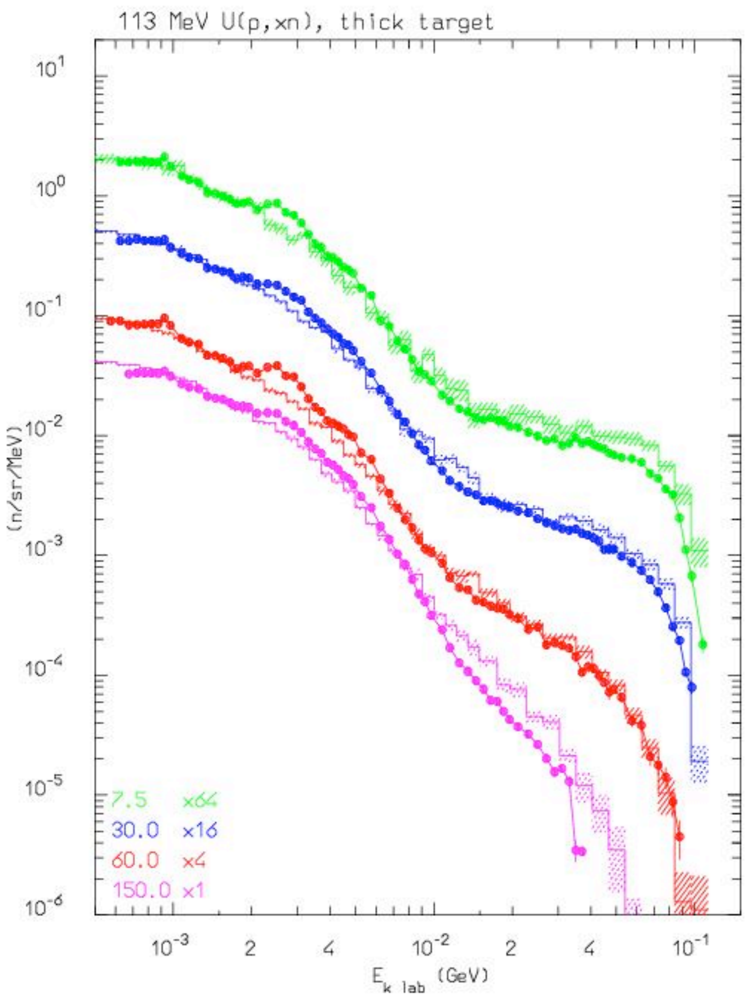
- FLUKA preequilibrium is based on GDH (M. Blann et al.) cast in a Monte Carlo form
- GDH: Exciton model, r, E_f are "local" averages on the trajectory and constrained state densities are used for the lowest lying configurations.
- Modification of GDH in FLUKA:
  - cross section s_{inv} from systematics
  - Correlation /coherence length/ hardcore effect on reinteractions
  - Constrained exciton state densities configurations 1p-ih, 2p-ih, 1p-2h, 2p-2h, 3p-1h and 3p-2h
  - True local r, E_f for the initial configuration, evolving into average
  - Non-isotropic angular distribution (fast particle approximation)

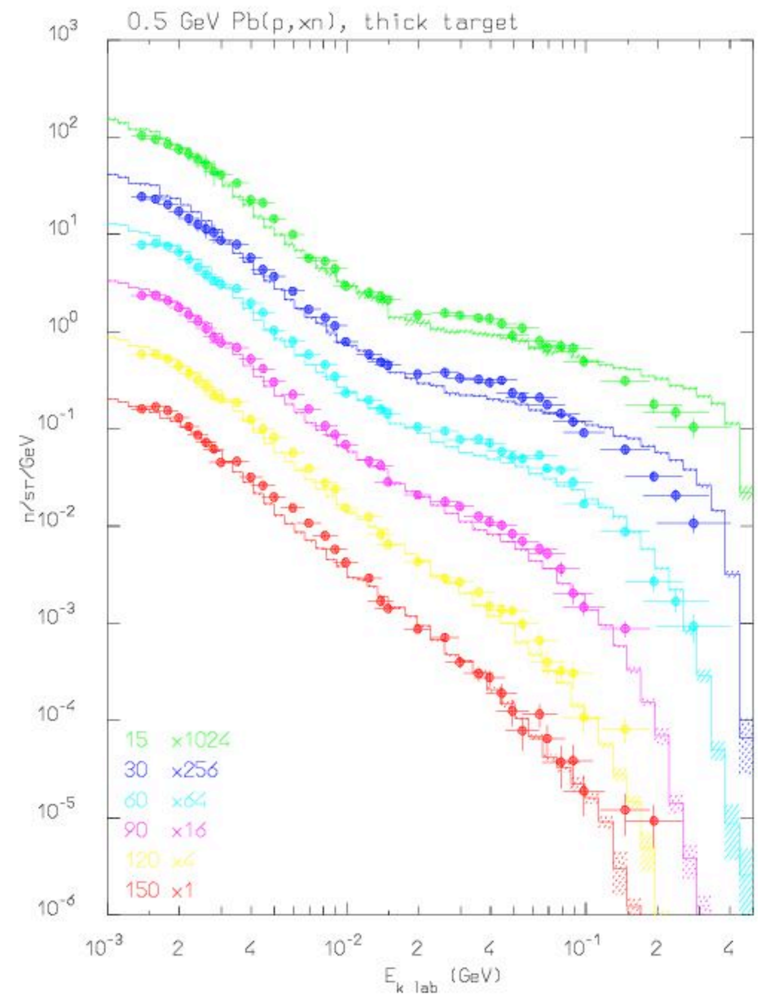
FLUKA

Equilibrium particle emission

- **Evaporation**: Weisskopf-Ewing approach
  - 600 possible emitted particles/states (A<25) with an extended evaporation/fragmentation formalism
  - Full level density formula
  - Inverse cross section with proper sub-barrier
  - Analytic solution for the emission widths
  - Emission energies from the width expression with no approximations
  - New energy dependent self-consistent evaporation level densities (IAEA recommendations)
  - New pairing energies consistent with the above point
  - Extension of mass tables till A=330 using available offline calculations
  - New shell corrections coherent with the new masses
- **Fission**:
  - Actinide fission done on first principles
  - New fission barrier calculations (following Myers & Swiatecki)
  - Fission level density enhancement at saddle point washing out with excitation energy (following IAEA recommendations)
  - Fission product widths and asymmetric versus symmetric probabilities better parameterized
- **Fermi Break-up** for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- γ **de-excitation**: statistical + rotational + tabulated levels

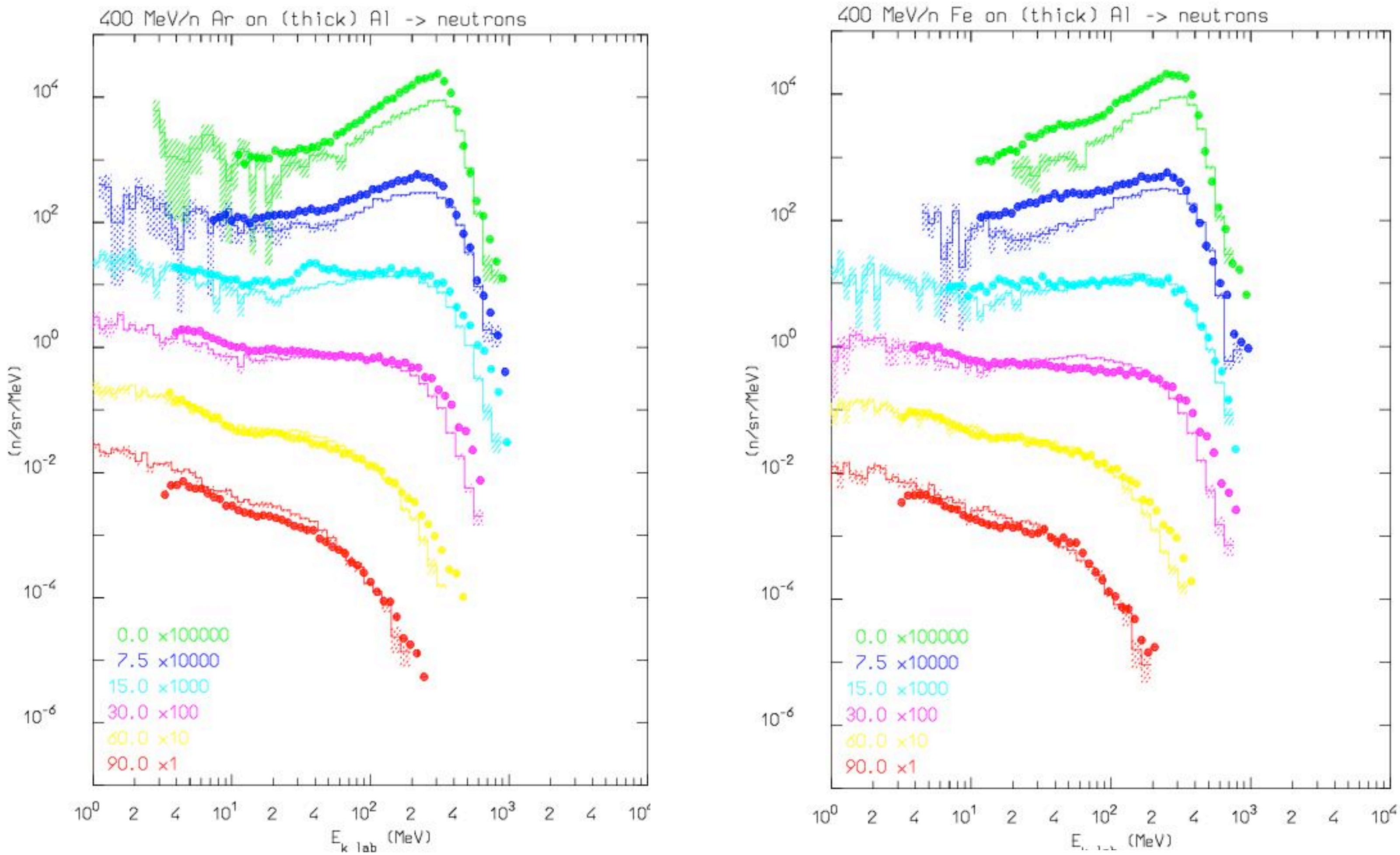
Thick target example





Neutron 2-differential distributions from protons on stopping-length targets:
113 MeV on U (left) and 500 MeV on Pb (right).
Exp. data from Meier et al., Nucl. Sci. Eng. 110, 299 (1992) and Meigo et al., JAERI-Conf. 95-008

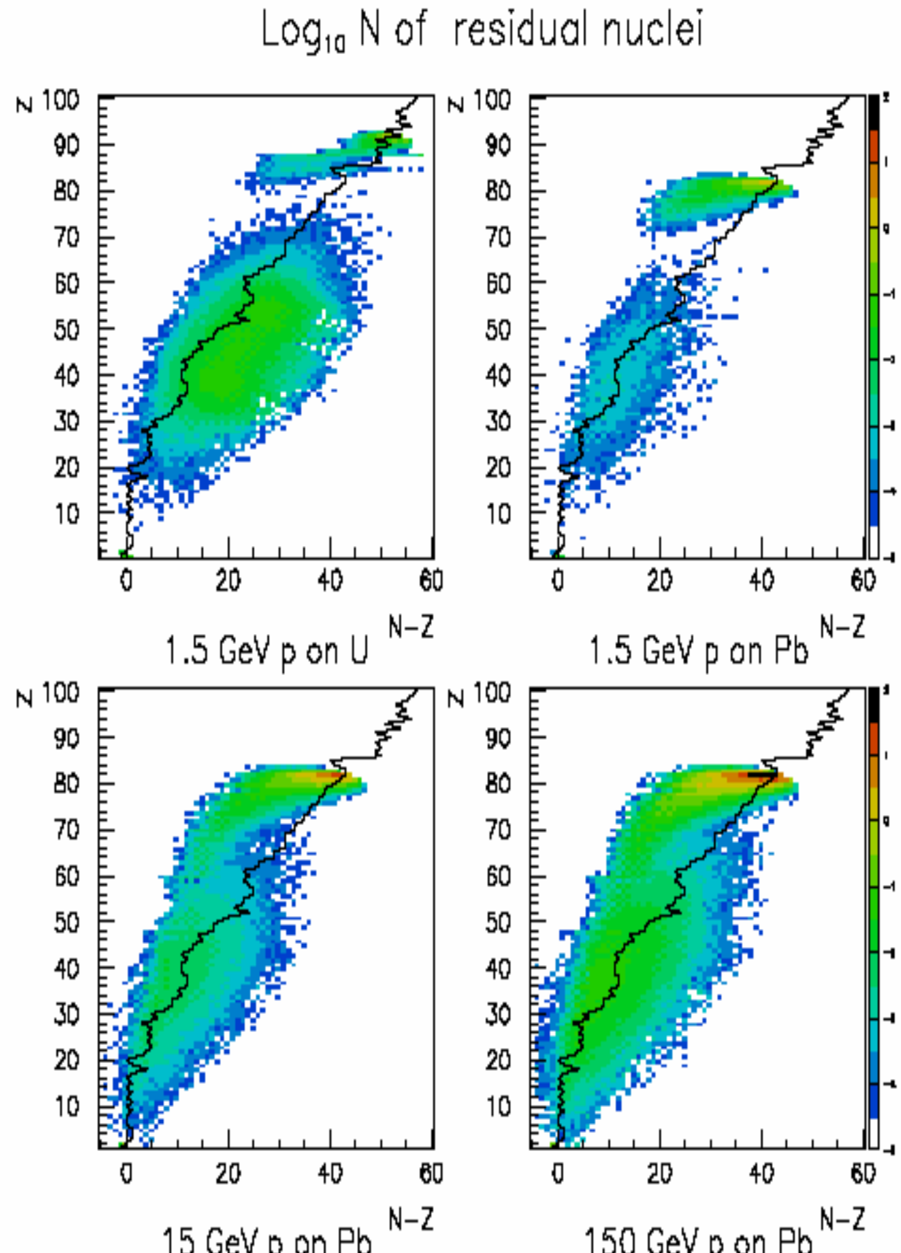
FLUKA with modified RQMD-2.4



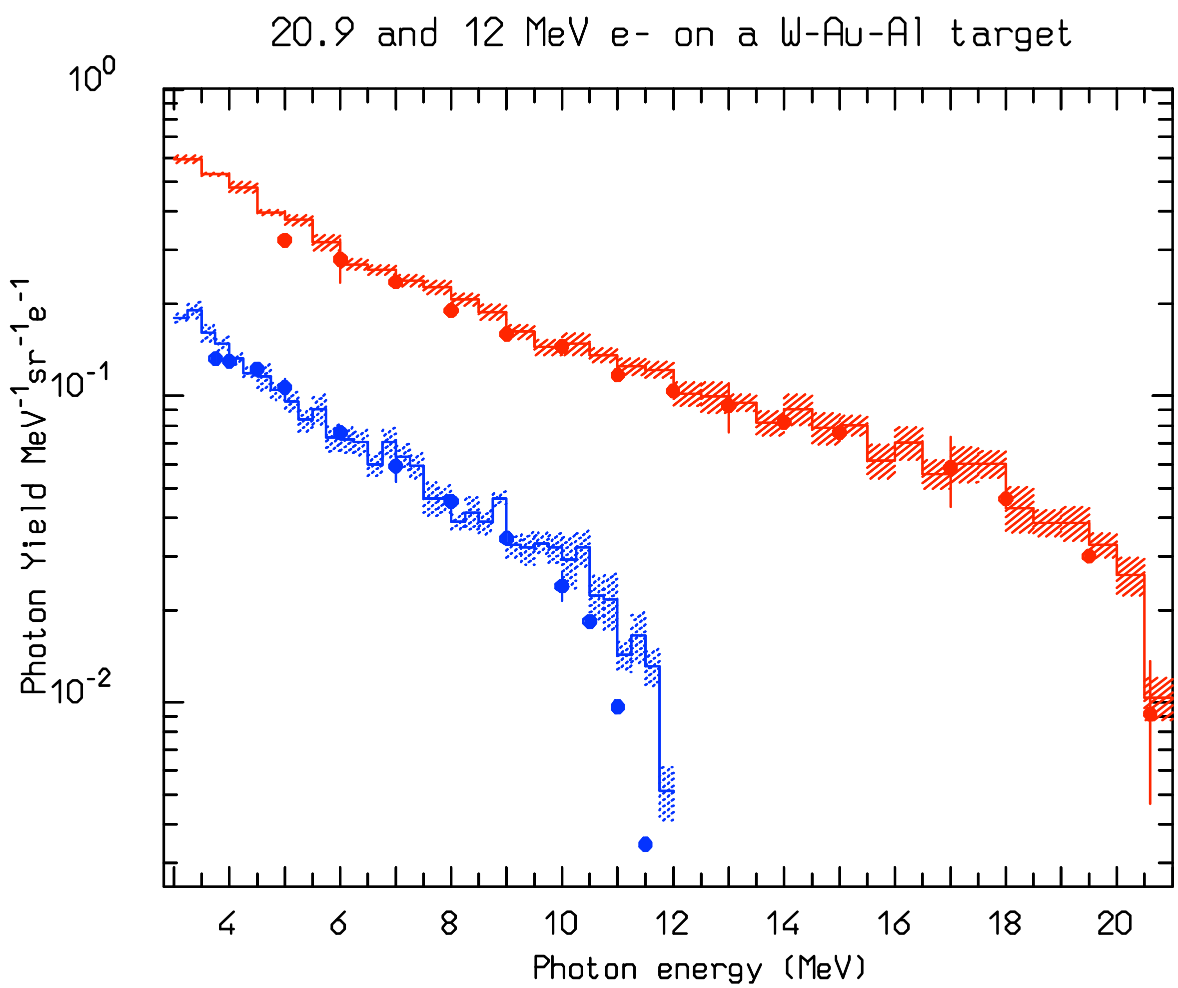
2-differential neutron yield by 400 MeV/n Ar (left) and Fe (right) ions on thick Al targets
Histogram: FLUKA. Experimental data points: Phys. Rev. C62, 044615 (2000)

Residual Nuclei

- The production of residuals is the result of the last step of the nuclear reaction, thus it is influenced by all the previous stages
- Residual mass distributions are very well reproduced
- Residuals near to the compound mass are usually well reproduced
- However, the production of specific isotopes may be influenced by additional problems which have little or no impact on the emitted particle spectra (Sensitive to details of evaporation, Nuclear structure effects, Lack of spin-parity dependent



Bremsstrahlung: benchmark

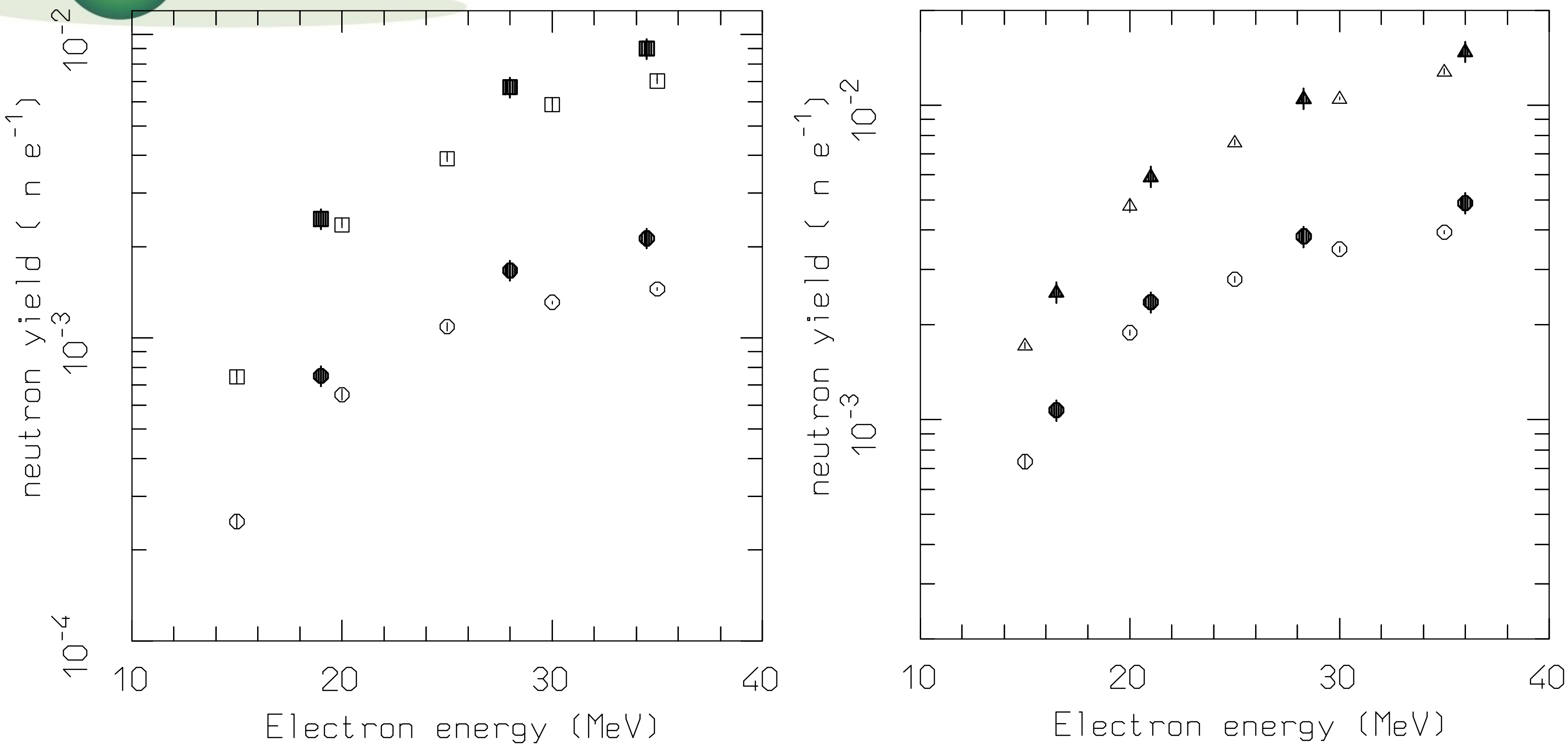


12 and 20.9 MeV electrons on a W-Au-Al target,

bremsstrahlung photon spectra in the forward direction

measured (dots) and simulated (histos)

Photonuclear Interactions:



Yield of neutrons per incident electron as a function of initial e^- energy. Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))

Left: Pb, 1.01 X_0 (lower points) and 5.93 X_0 (upper)

Right: U, 1.14 and 3.46 X_0

dE/dx atomic interactions

Discrete events

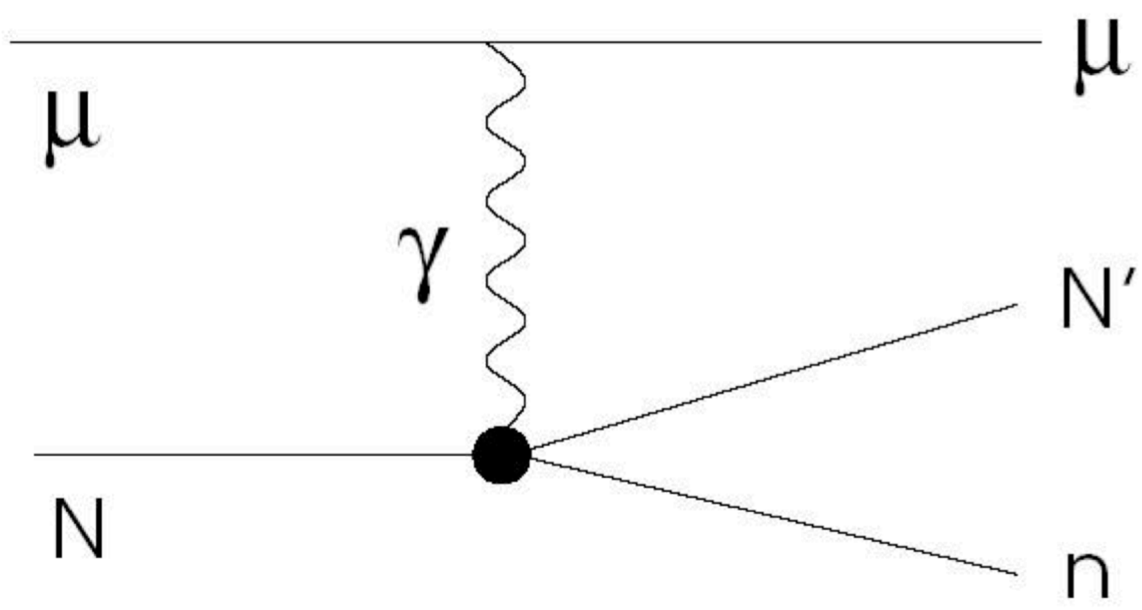
Delta-ray production above a user-defined threshold via

- Spin 0 or ½ δ-ray production (charged hadrons, μ's)
- Bhabha scattering (e^+)
- Møller scattering (e^-)

Continuous energy loss below threshold

- latest recommended values of ionization potential and density effect parameters implemented (Sternheimer, Berger & Seltzer), but can be overridden on user's request
- a new general approach to ionization fluctuations
  - based on general statistical properties of the cumulants of a distribution (Poisson distribution convoluted with $d\sigma/dE$)
  - integrals can be calculated analytically and exactly a priori (min CPU)
  - applicable to any kind of charged particle

Muon Photonuclear Reactions



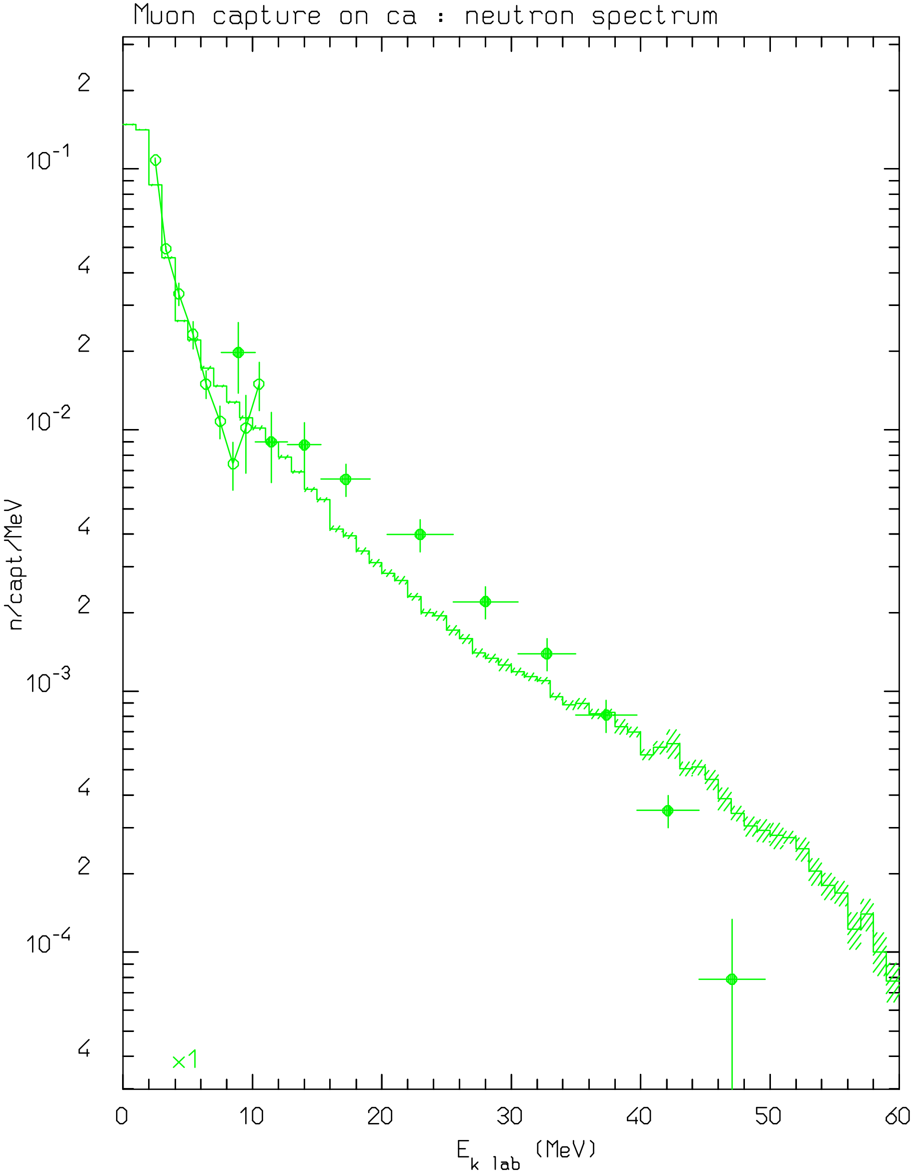
Schematic view of a μ hadronic interaction.

The interaction is mediated by a virtual photon.

The final state can be more complex

- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction.
- Nuclear screening is taken into account.
- Only Virtual Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models.
- Nuclear effects are the same as for hadron-nucleus interactions

Muon Capture II



Capture on Calcium

Dots: experimental data

(Columbia Univ. rep. NEVIS-172 (1969),
Phys. Rev. C7, 1037 (1973),
Yad. Fiz. 14, 624 (1972))

Histograms: FLUKA

Emitted:

0.62 neutrons/capture

0.27 protons/capture

Muon Capture

An exotic source of neutron background

- Basic weak process: $\mu^- + p \rightarrow \nu_\mu + n$
- μ^- at rest + atom → excited muonic atom → x-rays + g.s. muonic atom
- Competition between μ decay and μ capture by the nucleus
- In FLUKA: Goulard-Primakoff formula
- $\Lambda_c \approx Z_{eff}^4$, calculated Z_{eff}, Pauli blocking from fit to data

  $\Lambda_c/\Lambda_d = 9.2\cdot10^{-4}$ for H, 3.1 for Ar, 25.7 for Pb
- Nuclear environment (Fermi motion, reinteractions, deexcitation…) from the FLUKA intermediate-energy module PEANUT
- Slow projectile, low energy transfer (neutron E = 5 MeV on free p)
- Experimentally: high energy tails in n-spectra
- Beyond the simple one-body absorption: good results from addition of two-nucleon absorption

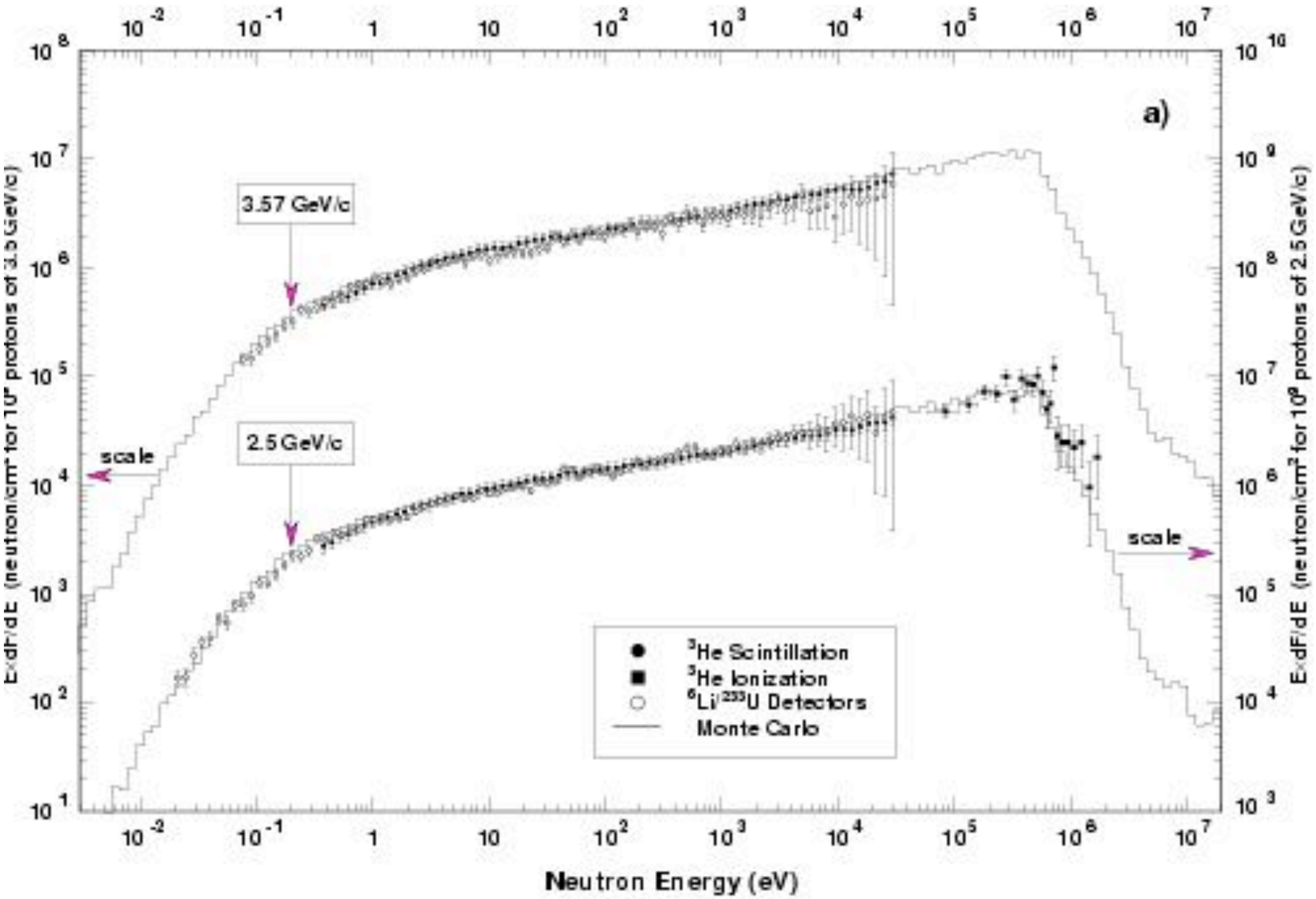
Low-energy neutron transport

In FLUKA, performed by a **multigroup algorithm**:

- Widely used in low-energy neutron transport codes (not only Monte Carlo, but also Discrete Ordinate codes)
- Energy range of interest is divided in discrete intervals "energy groups". In FLUKA, 260 groups.
- Elastic and inelastic reactions simulated not as exclusive processes, but by group-to-group transfer probabilities (down-scattering matrix)
- The scattering transfer probability between different groups is repres … ted at the (N

$$\sigma_s(g \circledR\ g', \mu) = \sum_{i=0}^{N} \frac{2i+1}{4\pi} P_i(\mu) \sigma_s^i(g \circledR\ g')$$

The TARC experiment



Protons ≅ 3 GeV/c

334 ton Pb target

fully instrumented

(64 detector holes)

Simulation:

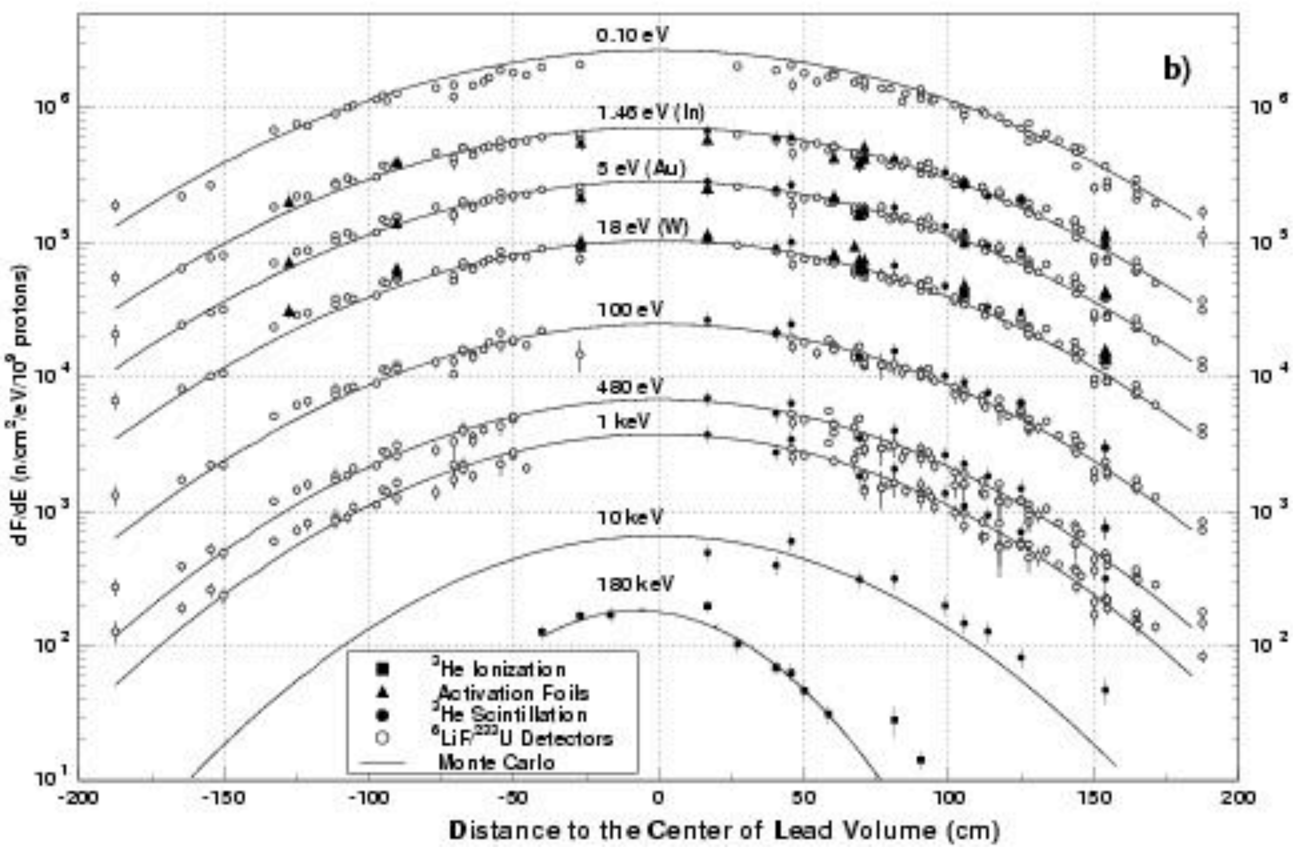
FLUKA + EA-MC

(C. Rubbia et al.)

PLB 458, 167 (1999)

NIM A478, 577 (2002)

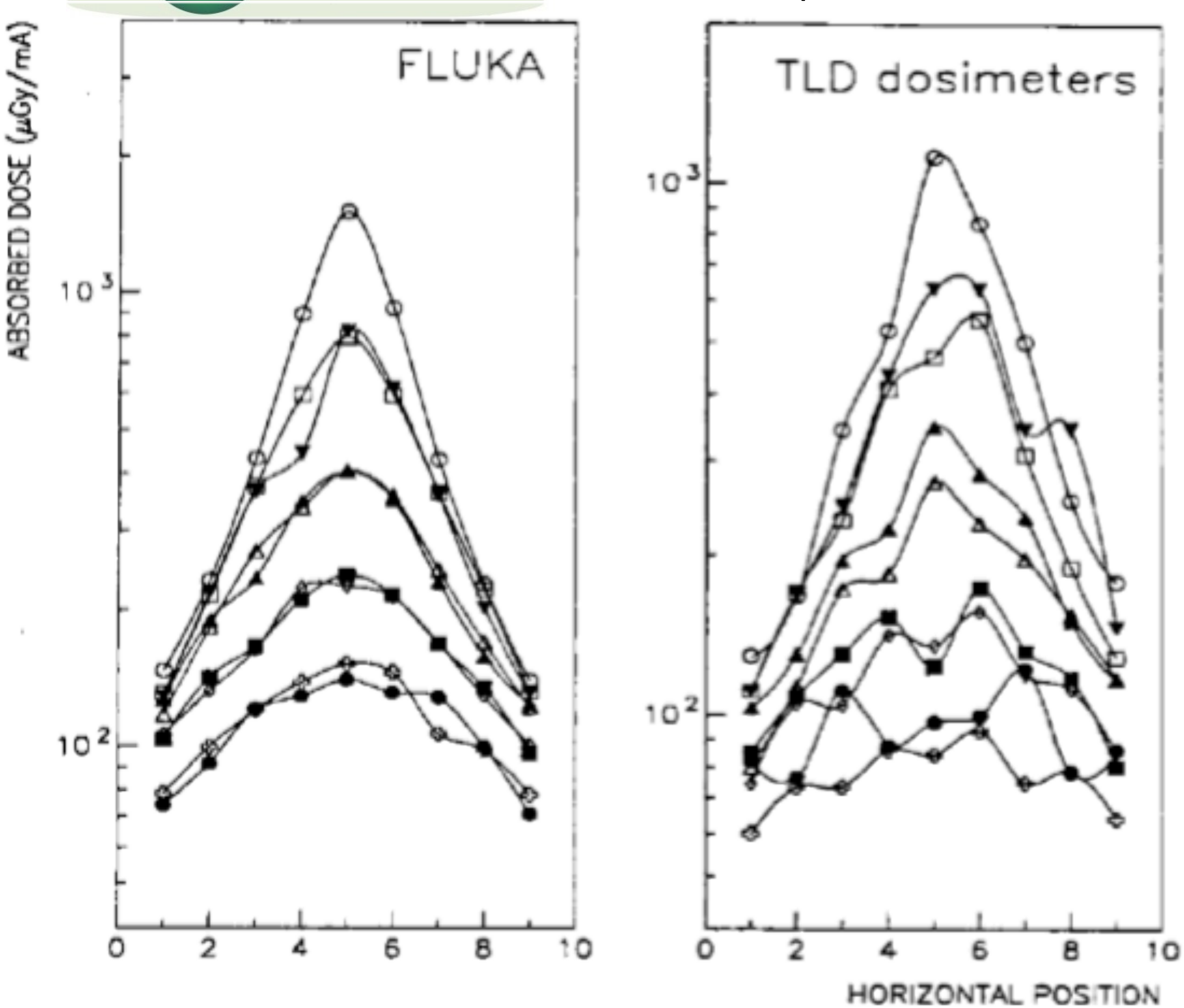
The TARC experiment



Measured and simulated neutron fluence distribution in space

Bremsstrahlung: benchmark III

Esposito et al., LNF 93-072



ADONE storage ring

1.5 GeV e^-

Bremsstrahlung on the residual gas in a straight section

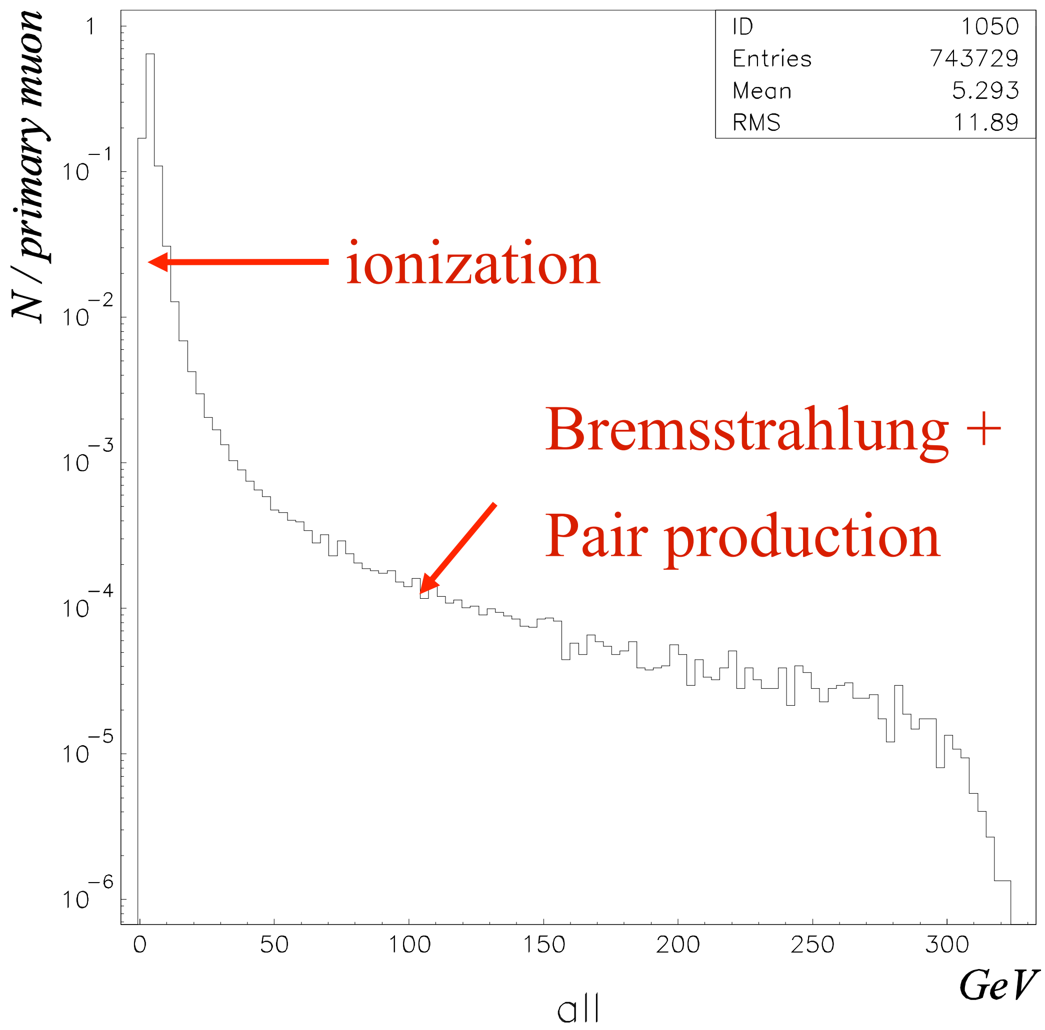
Measured with TLD's matrices

Here: dose vs. horizontal position at different vertical positions ,

Distance from straight section: 218 cm

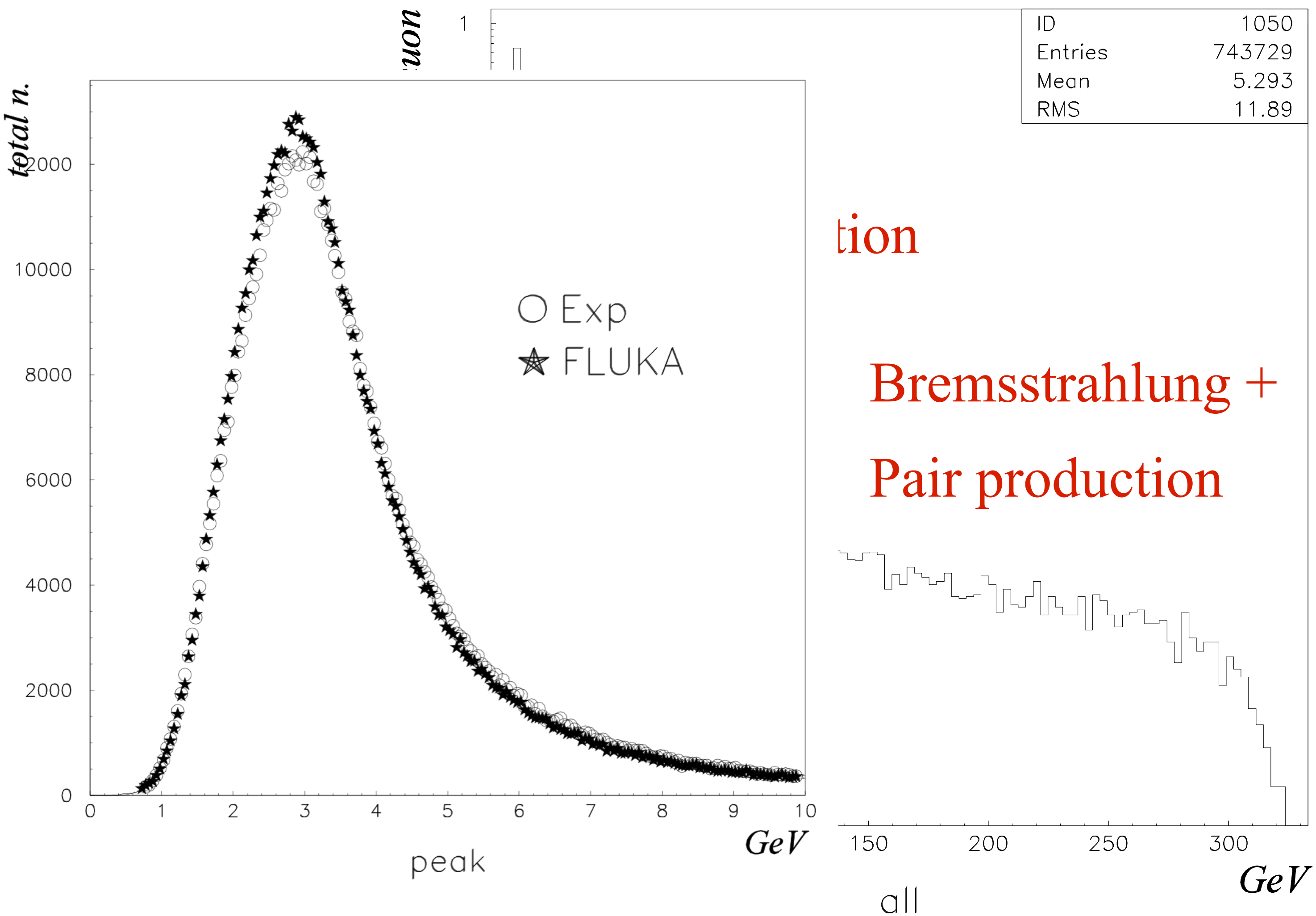
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



Energy Deposition spectrum in the Atlas tile-calorimeter prototype

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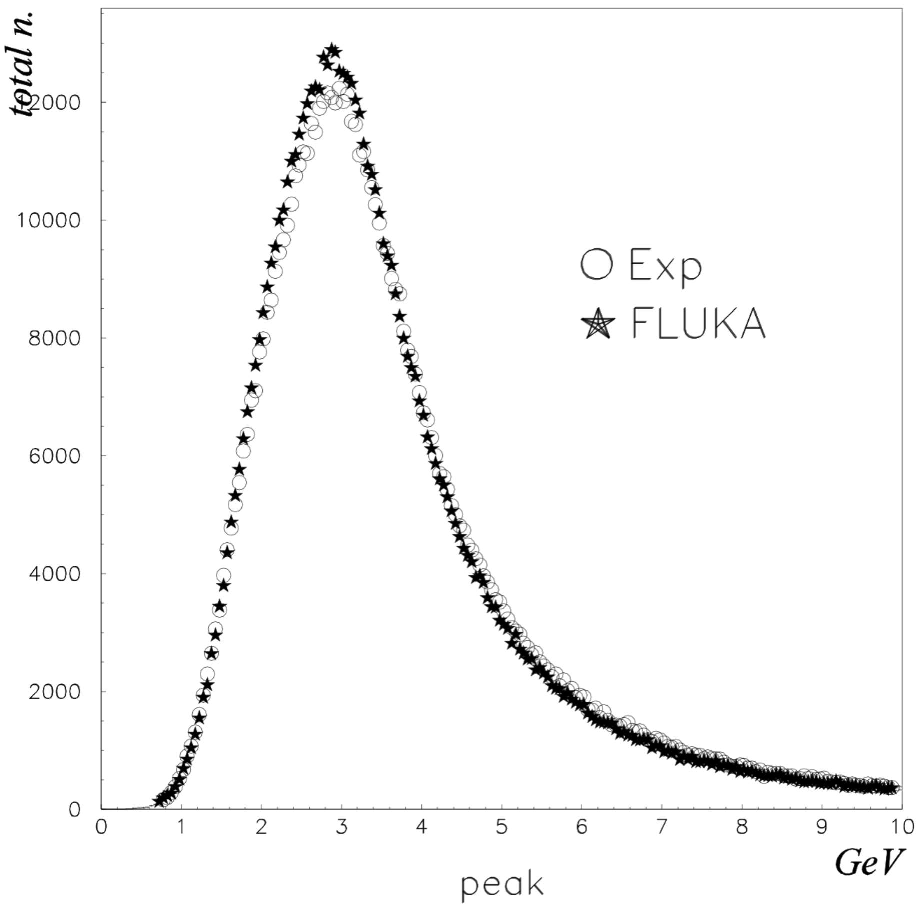
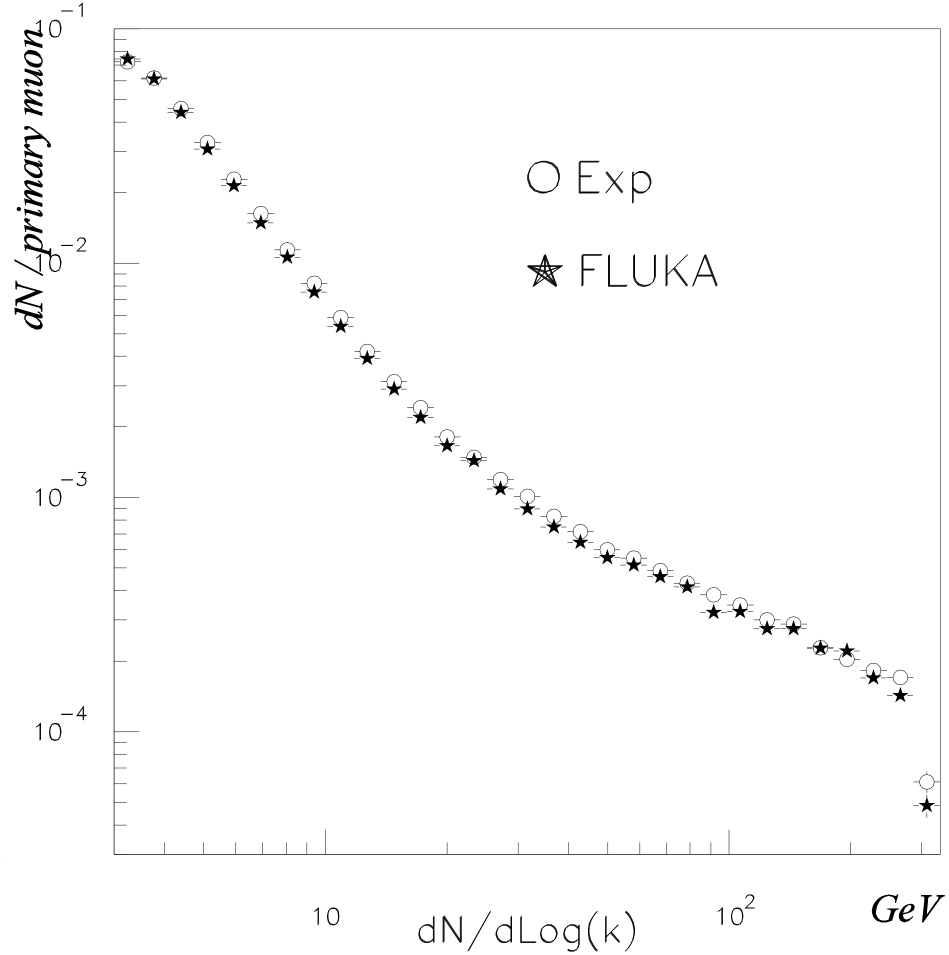
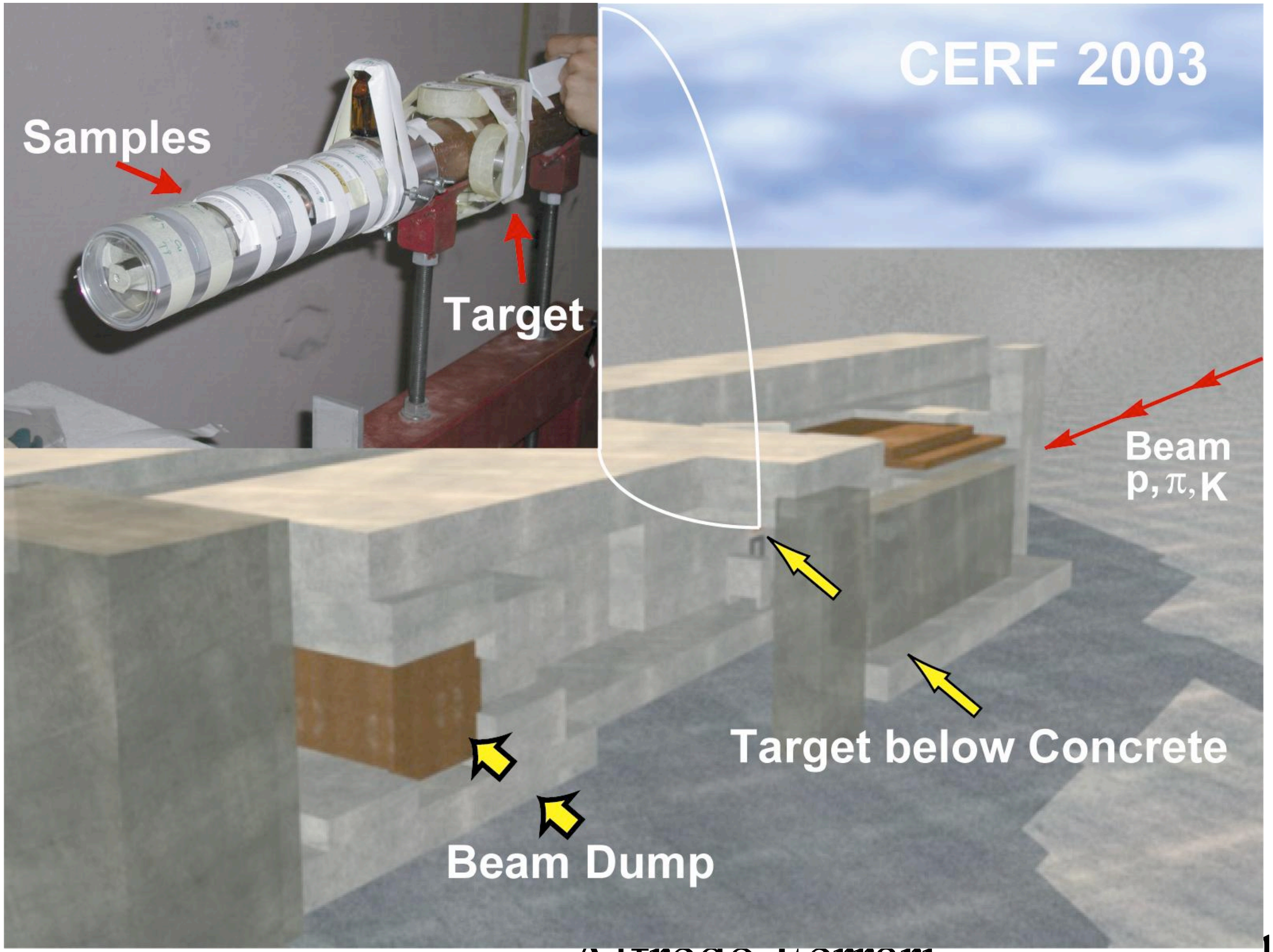




CERN-EU High-Energy Reference Field (CERF) facility



Location of Samples:

Behind a 50 cm long, 7 cm diameter copper target, centred with the beam axis

Analog Monte Carlo

Pros

- samples from actual physical phase space distributions
- predicts average quantities and all statistical moments of any order
- preserves correlations (provided the physics is correct)
- reproduces fluctuations (-//-)
- is almost safe and sometimes can be used as a "black box"

Cons

- is inefficient and converges very slowly
- fails to predict important contributions due to rare events

Biased Monte Carlo

- samples from artificial distributions, and applies a weight to the particles to correct for the bias
- predicts average quantities but not the higher moments (on the contrary the goal is to minimize the second moment!)

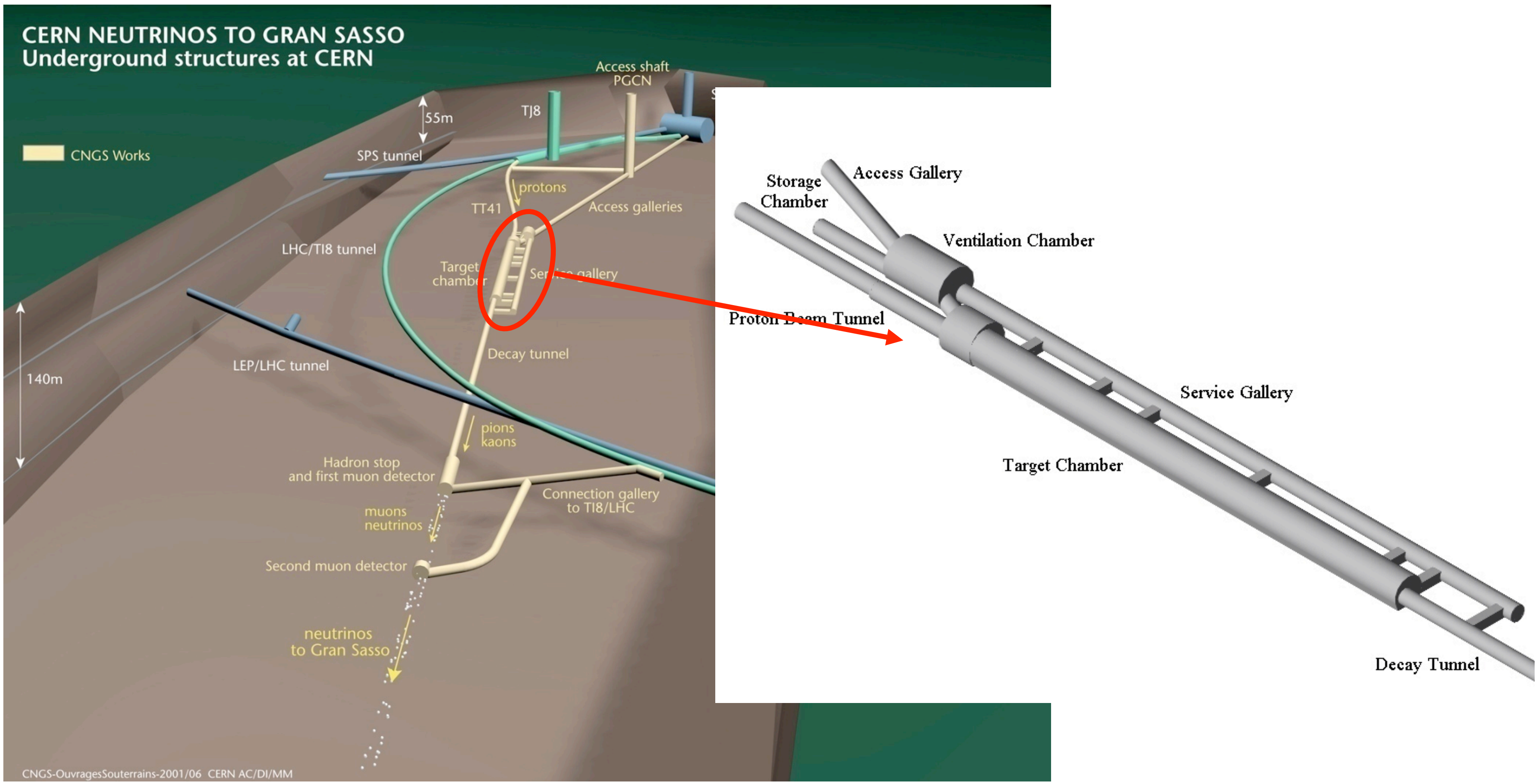
Pros

- same mean with smaller variance $\Rightarrow$ faster convergence
- allows sometimes to obtain acceptable statistics where an analog Monte Carlo would take years of CPU time to converge

Cons

- cannot reproduce correlations and fluctuations
- with a few exceptions, requires physical judgment, experience and a good understanding of the problem
- in general, a user does not get the definitive result after the first run, but needs to do a series of test runs in order to optimize the biasing parameters

Applications – *CNGS*



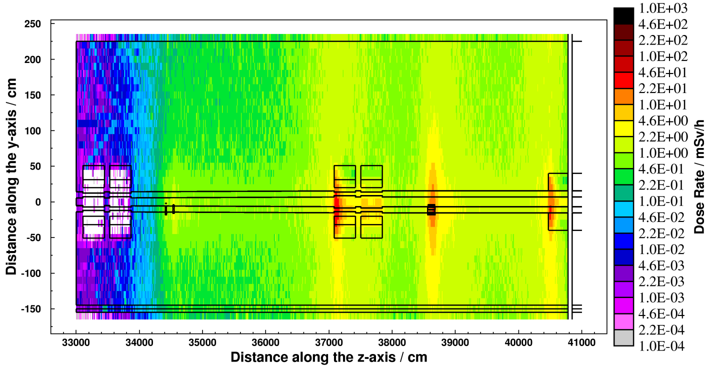
Applications – LHC collimation region

Cooling time

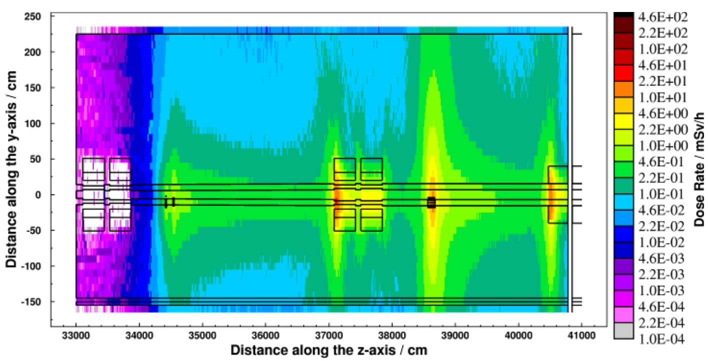
Residual dose rate (mSv/h)

after one year of operation

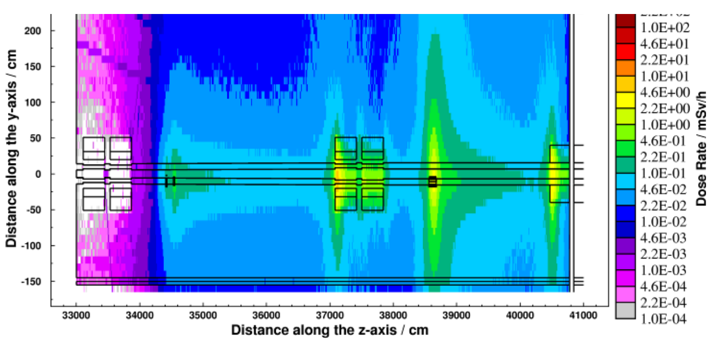
8 hours

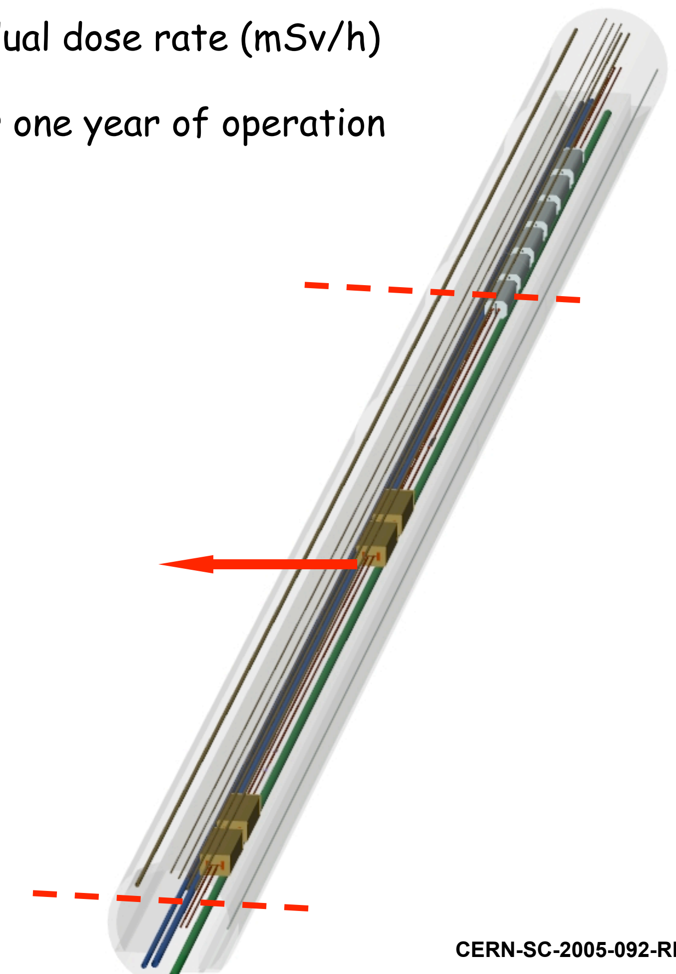


1 week



4 months





CERN-SC-2005-092-RP-TN

REMANENT DOSE RATE MAPS OF THE LHC BETATRON CLEANING INSERTION (IR7)

M. Brugger, D. Forkel-Wirth, S. Roesler

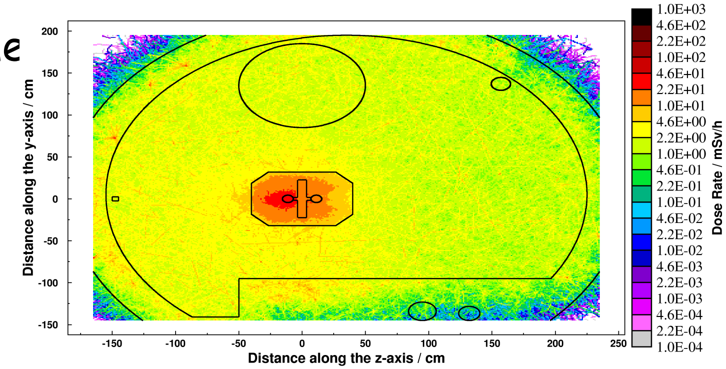
Applications – LHC collimation region

Residual dose rate (mSv/h)

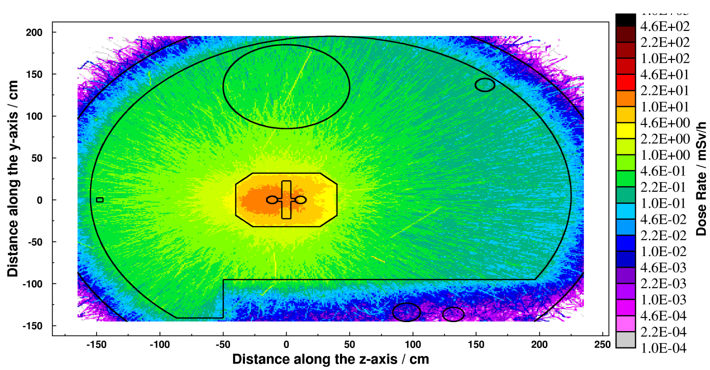
after one year of operation

Cooling time

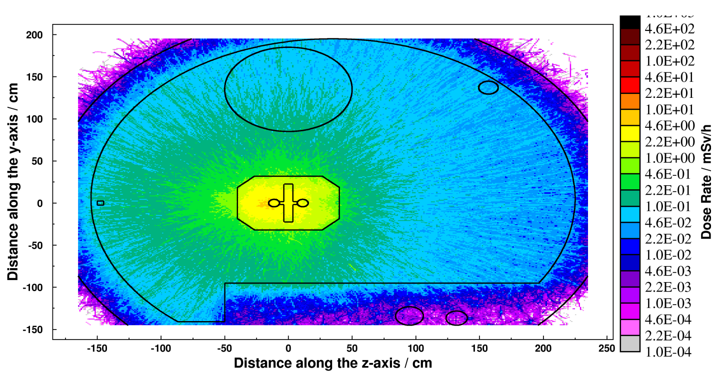
8 hours

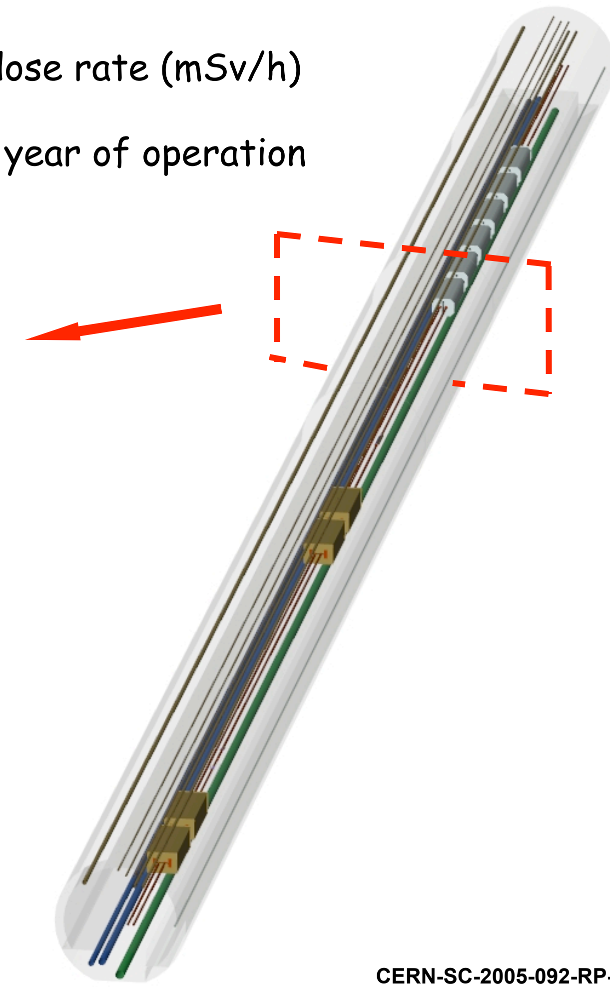


1 week



4 months





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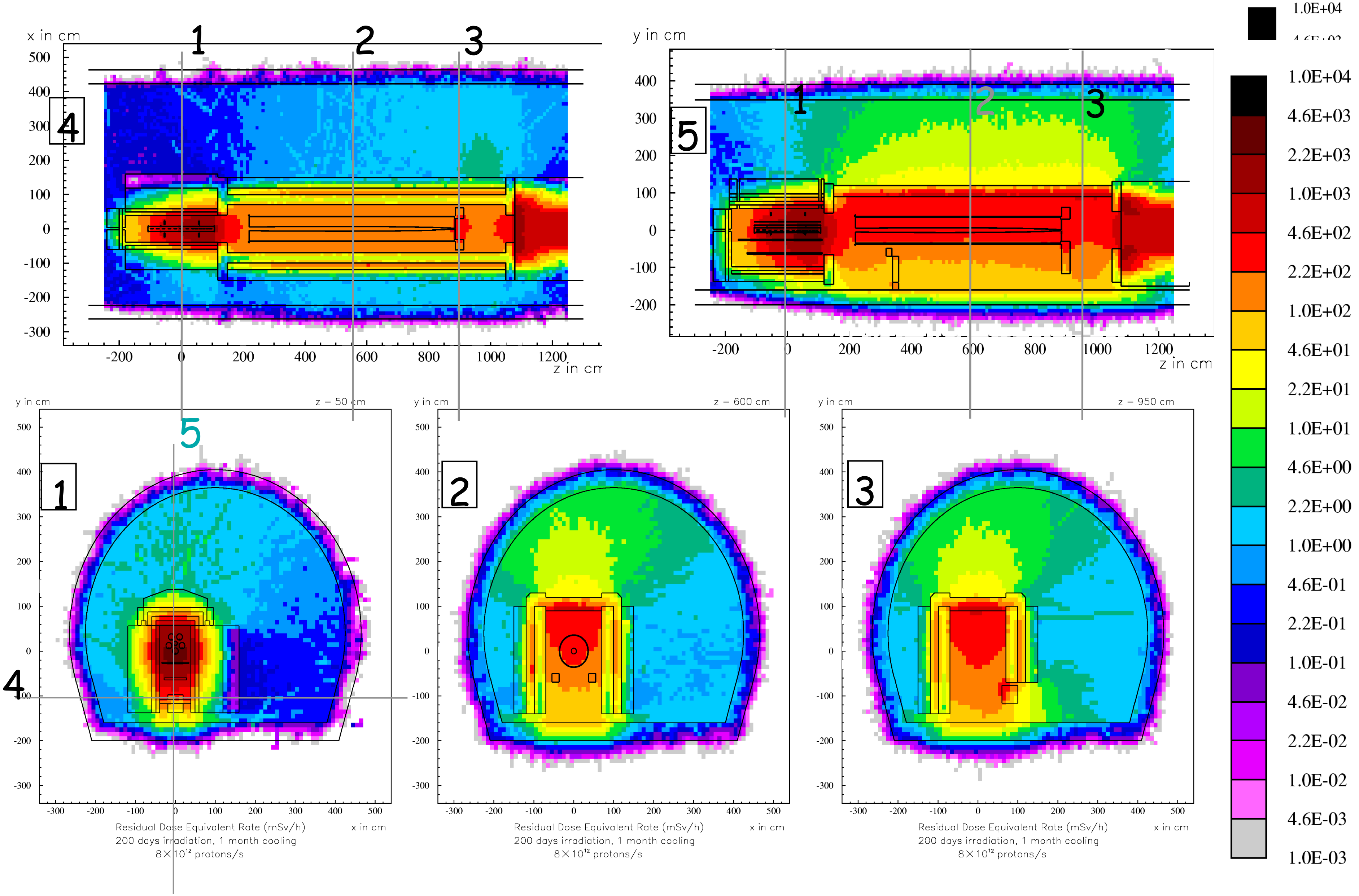
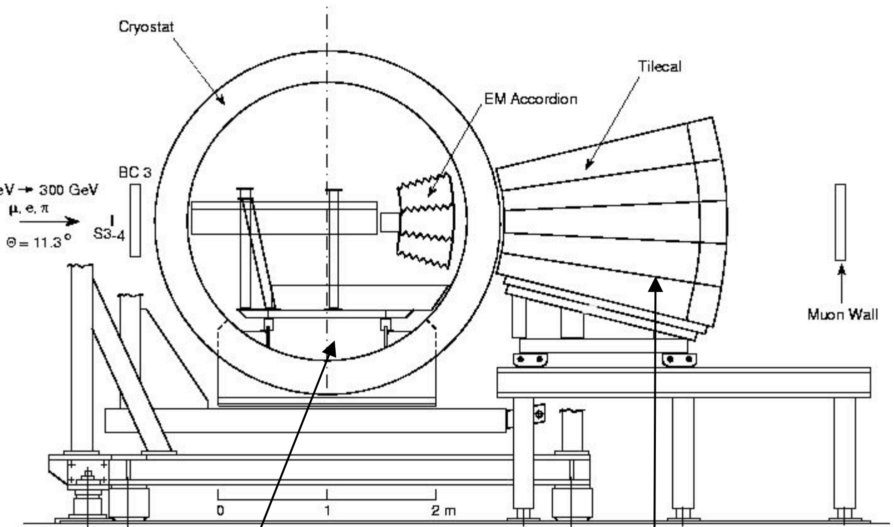


Combined calorimeter test

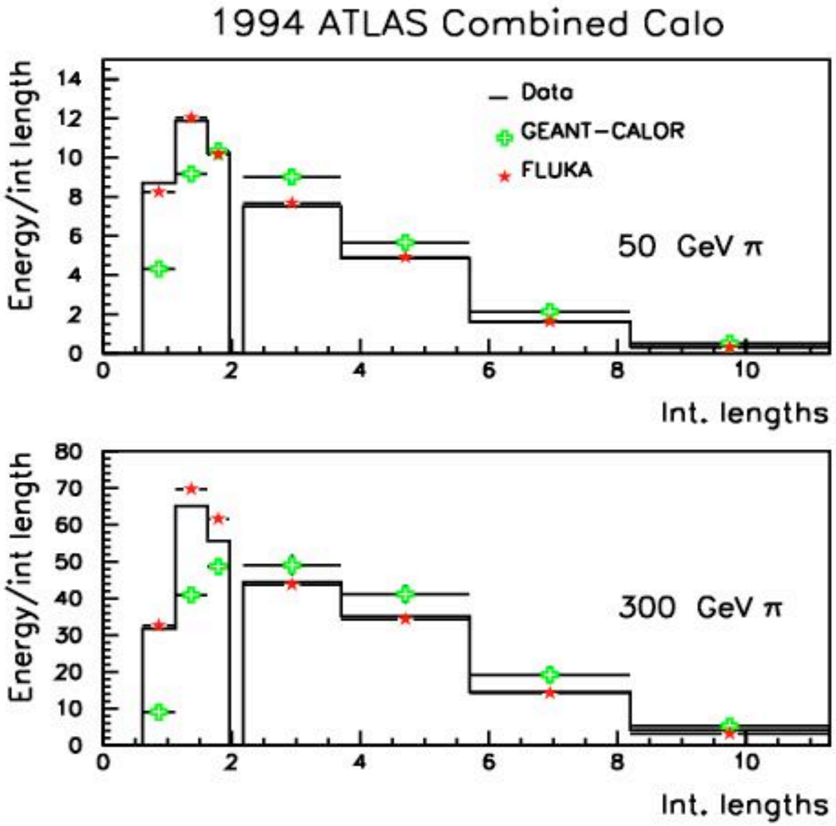
Layout of the experimental set-up (NIM A387,333(1997), NIM A449,461 (2000))



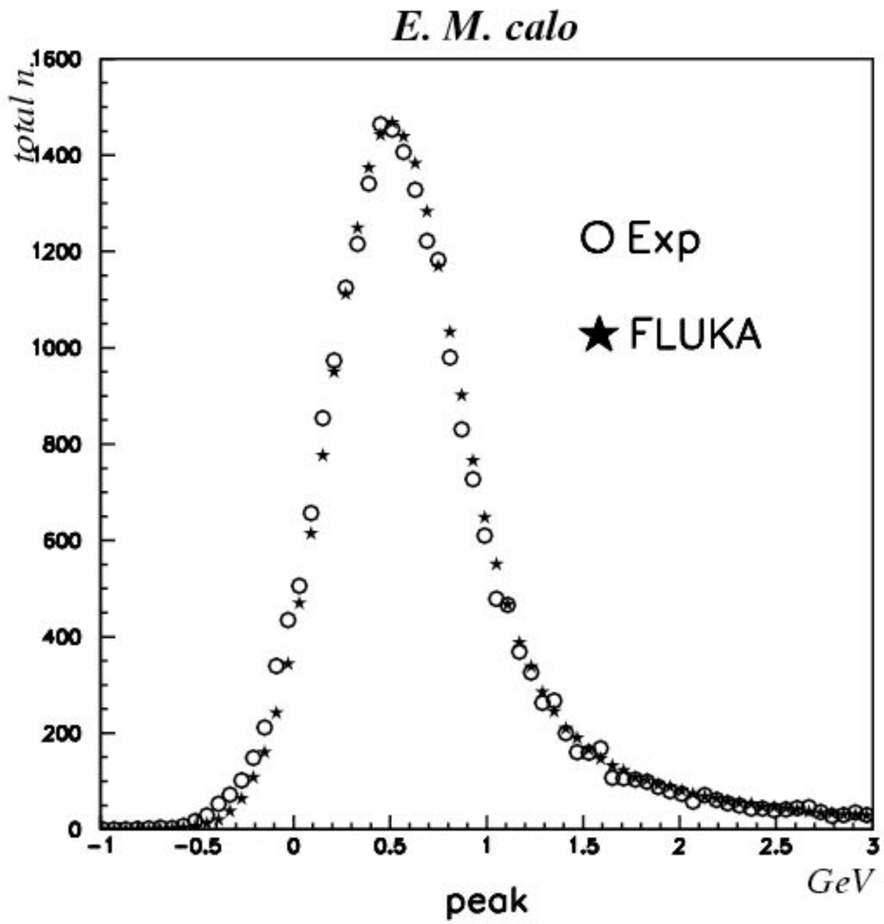
EM Pb-LAr calorimeter

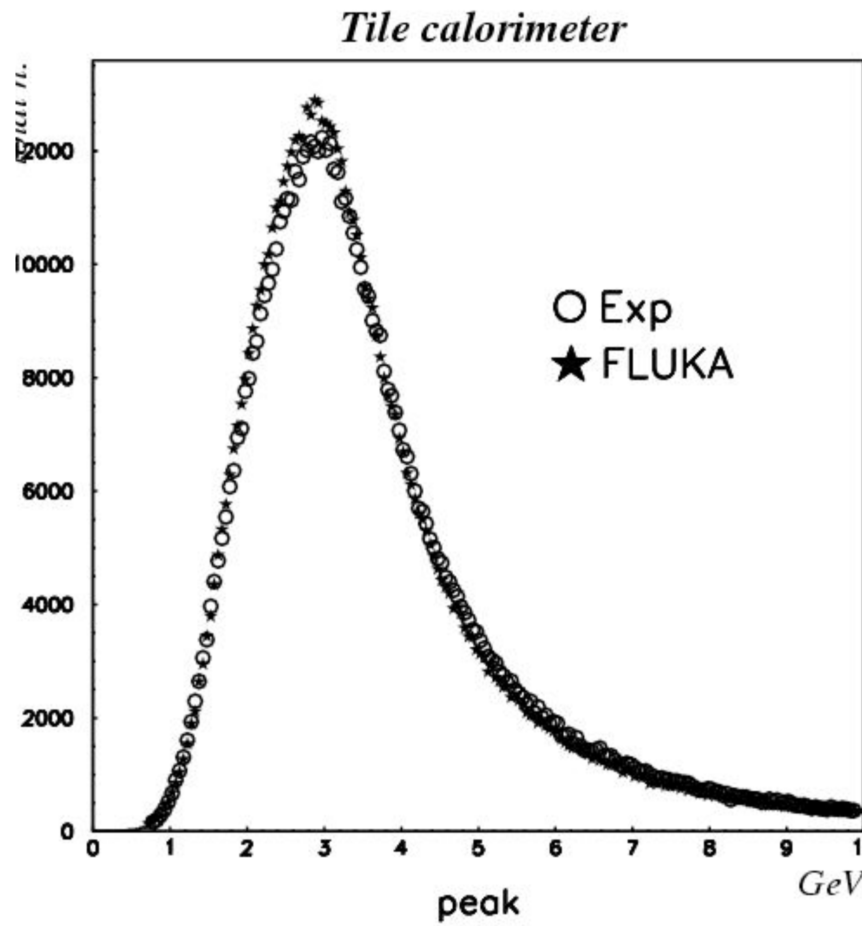
hadronic Fe-scintillating-tile calorimeter

Longitudinal hadron shower profile



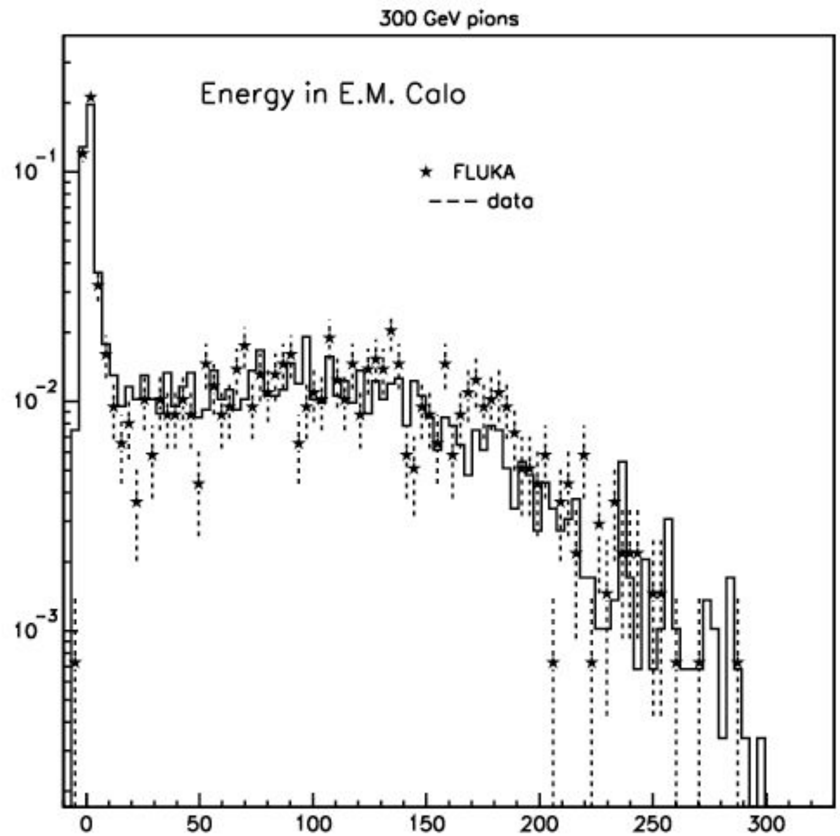
Combined calorimeter test



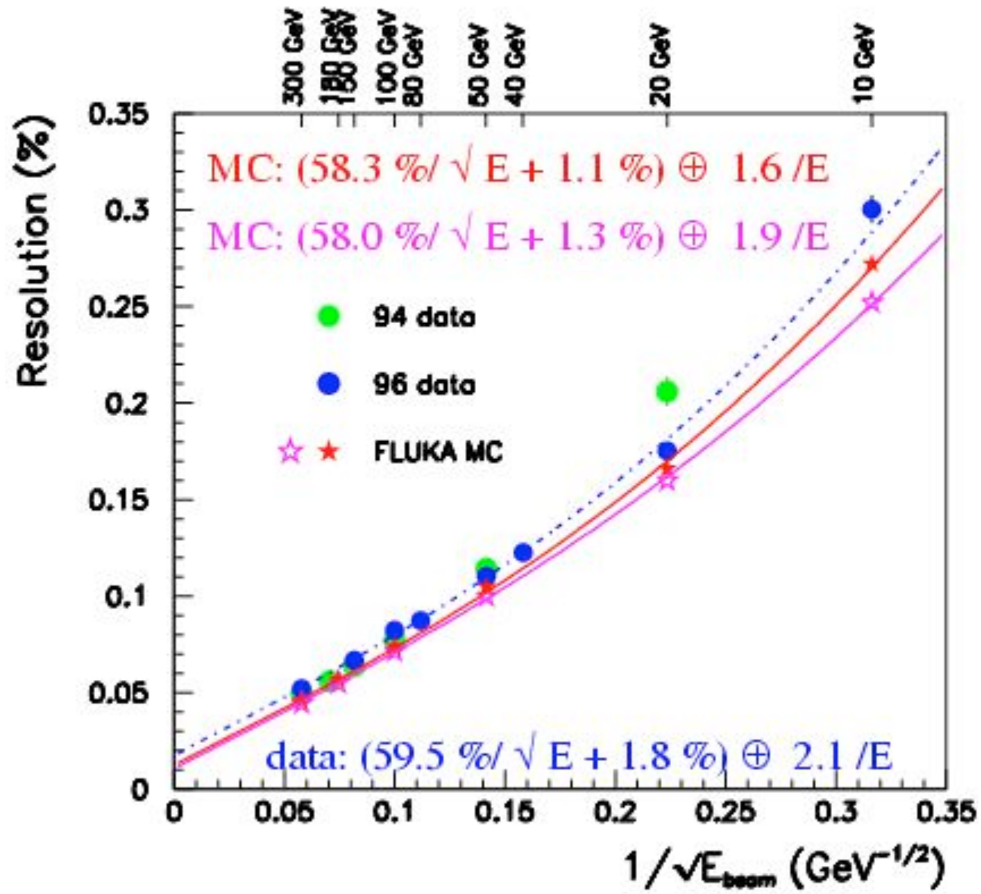


Muon signal in the two calorimeters (➔ e/μ faithfully reproduced)

Combined calorimeter test



Energy spectrum in EM calo



Energy resolution

FLUKA and Cosmic Ray physics: Atmospheric Showers

Two different streams:

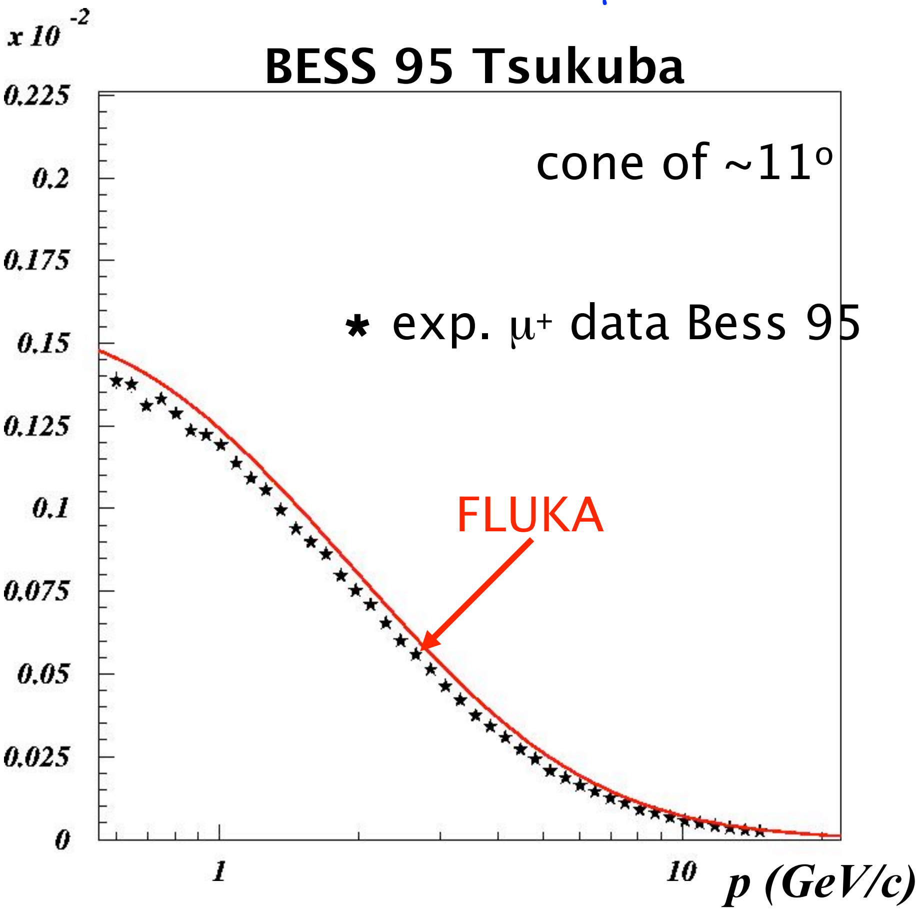
- Basic research on Cosmic Ray physics (muons, neutrinos, EAS, underground physics,….)
- Application to dosimetry in civil aviation (DOSMAX Collaboration: Dosimetry of Aircrew Exposure to Radiation During Solar Maximum)

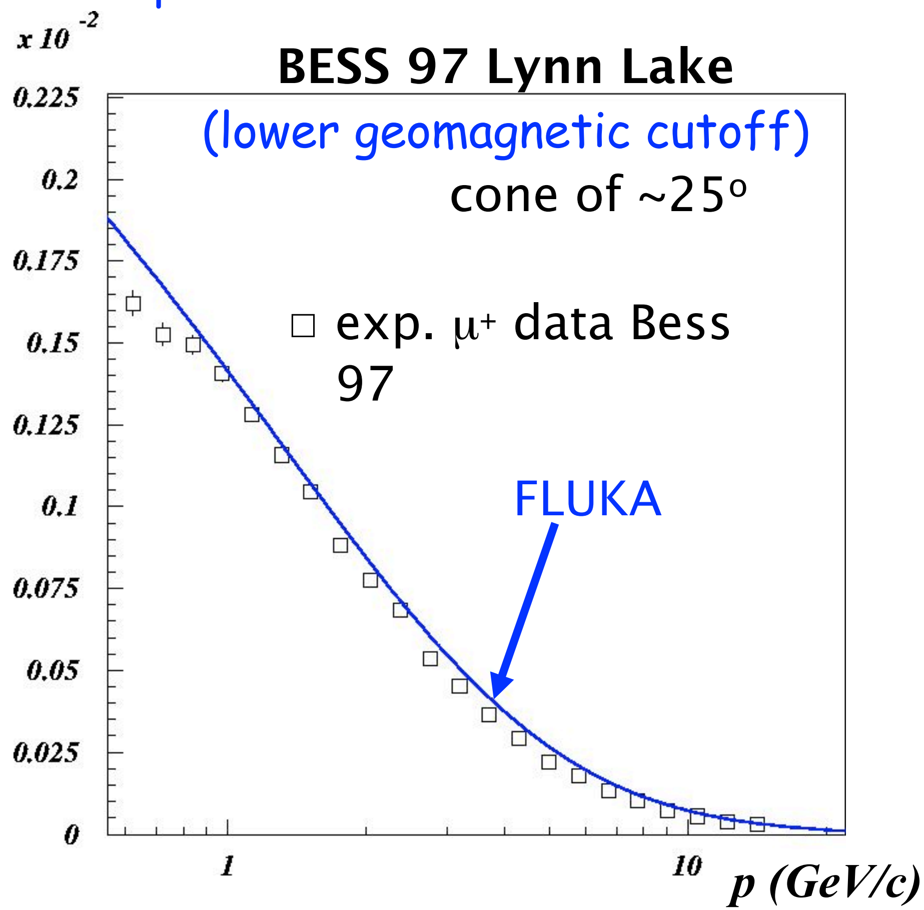
Available dedicated FLUKA library + additional packages including:

- Primary spectra from Z = 1 to Z = 28 (derived from NASA and updated to most recent measurements.)
- Solar Modulation model (correlated to neutron monitors)
- Atmospheric model (MSIS Mass-Spectrometer-Incoherent-Scatter)
- 3D geometry of Earth + atmosphere
- Geomagnetic model

An atmospheric muon benchmark

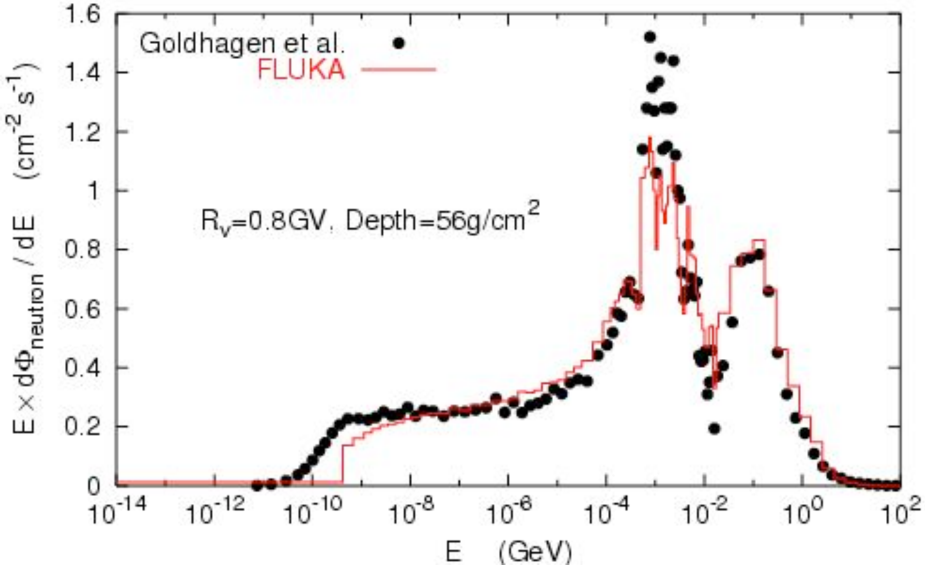
μ^+ from the BESS experiment





Primary flux normalized to the AMS/BESS data

Neutrons on the ER-2 plane at 21 km altitude



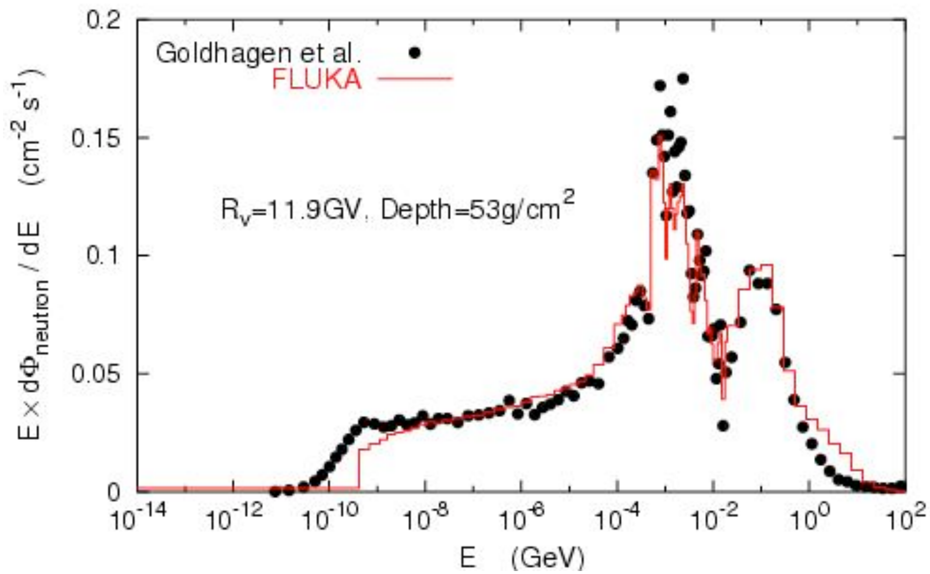
Measurements:

Goldhagen et al., NIM A476, 42 (2002)

Note one order of magnitude difference depending on latitude

FLUKA calculations:

Roesler et al., Rad. Prot. Dosim. 98, 367 (2002)



In beam treatment control with PET

Final goal:

- Simulation of β^+ emitters generated during the irradiation
- In-beam treatment plan verification with PET

Work in progress: FLUKA validation

- Comparison with experimental data on fragment production (Shall et al.)
  - ^{12}C, ^{14}N, ^{16}O beams, 675 MeV/A
  - Adjustable water column 0-25.5 cm
  - Z spectra of escaping fragments for $Z > 4$
  - Cumulative yield of light fragments
  - Simulation: corrections applied for angular acceptance and for material in the beam upstream the water target
- Comparison with treatment planning code TRiP98 on Bragg peak position and width, 80-430 MeV/u ion beams

Radioactivity produced by μ

Among the goals of the CTF experiment:
learning how to reduce the cosmogenic background

the ^{11}C problem: Muon-induced ^{11}C: 7.5 counts/day

Required reduction factor > 10

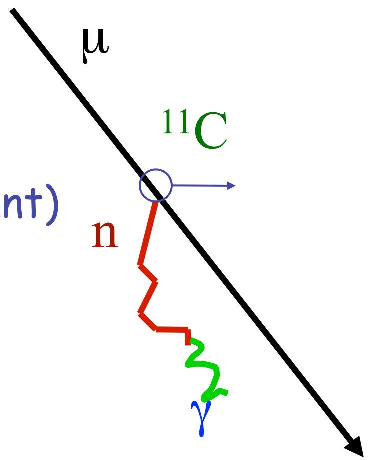
Goal: tagging and removing ^{11}C <u>event by event</u>!!!

$$\mu + {}^{12}C \rightarrow {}^{11}C + n$$

(this is not the only reaction producing ^{11}C, but the most important)

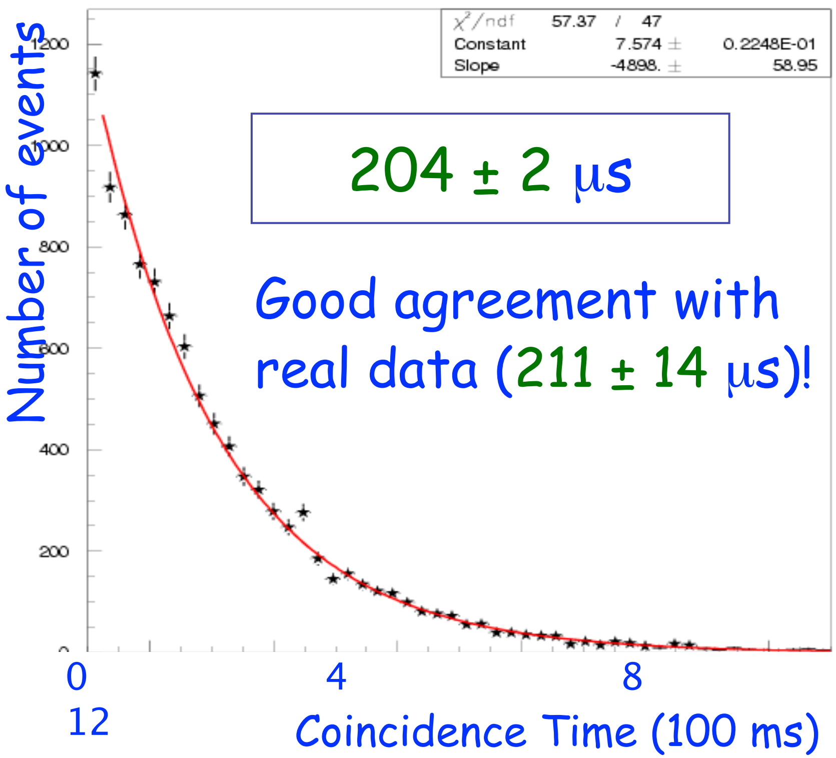
The γ produced in the neutron capture is used to tag the event

$$n + p \rightarrow d + \gamma \quad \begin{cases} \tau \sim 200\ \mu s \\ E = 2.2\ \text{MeV} \end{cases}$$



FLUKA results

Neutron capture in scintillator and water



The total pathlength of each kind of secondary, differential in energy, was calculated with FLUKA and folded with the ^{11}C production cross section.

Similar calculations were also done for a different experiment[(1)]

^{11}C production rate $[10^{-4} / \mu / m]$

	100 GeV[(1)]	190 GeV[(1)]	320 GeV
Meas.:	22.9±1.8	36.0±2.3	51.8±5.0
Calc.:	28.3±1.9	41.3±3.1	59.9

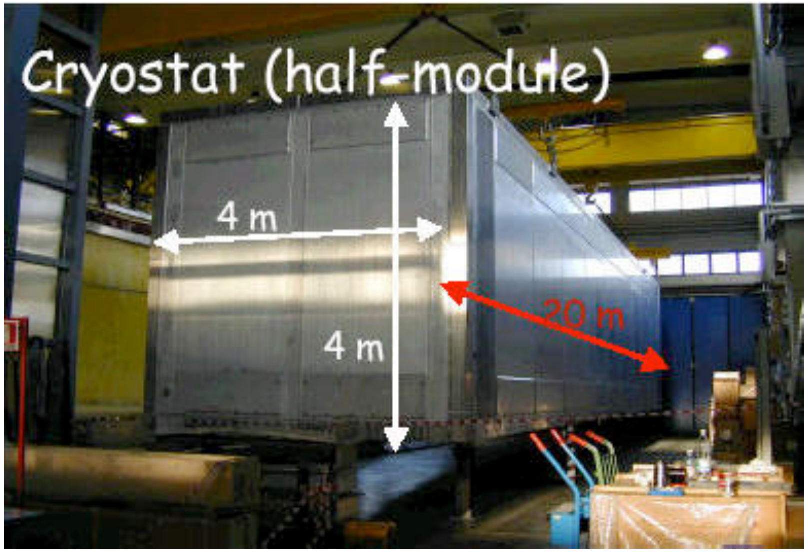
[(1)] T. Hagner et al., Astropart. Phys. 14, 33 (2000)

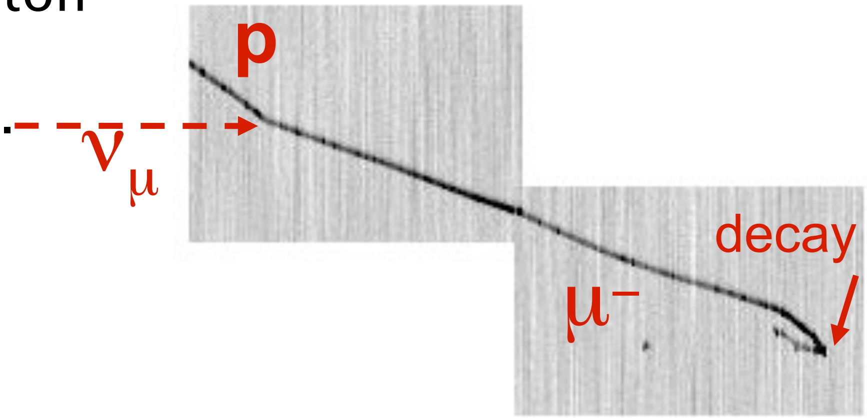
Galbiati et al., arXiv:hep-ph/0411002 (2004)

ICARUS: Simulation

FLUKA is used in ICARUS at Gran Sasso laboratory for different applications:

- full detector simulation
- atmospheric neutrino generation and interactions
- neutrinos from CNGS beam
- interaction of solar and SuperNovae neutrinos
- generation and detection of proton decay
- calculation the expected rate vs. multiplicity of underground muon events





High Energy Cosmic Ray Physics

with S. Muraro, T. Rancati, ICARUS Collaboration

The aim is to predict multiple muon rates for different primary masses and energy within the framework of a unique simulation model

Four steps:

1) atmospheric shower generation
2) transport in Gran Sasso rock
3) folding with the detector (spatial randomization of event)
4) full simulation in ICARUS T600

Interaction model: **FLUKA + DPMJET for nucleus-nucleus collisions Secondary threshold = 1 TeV**

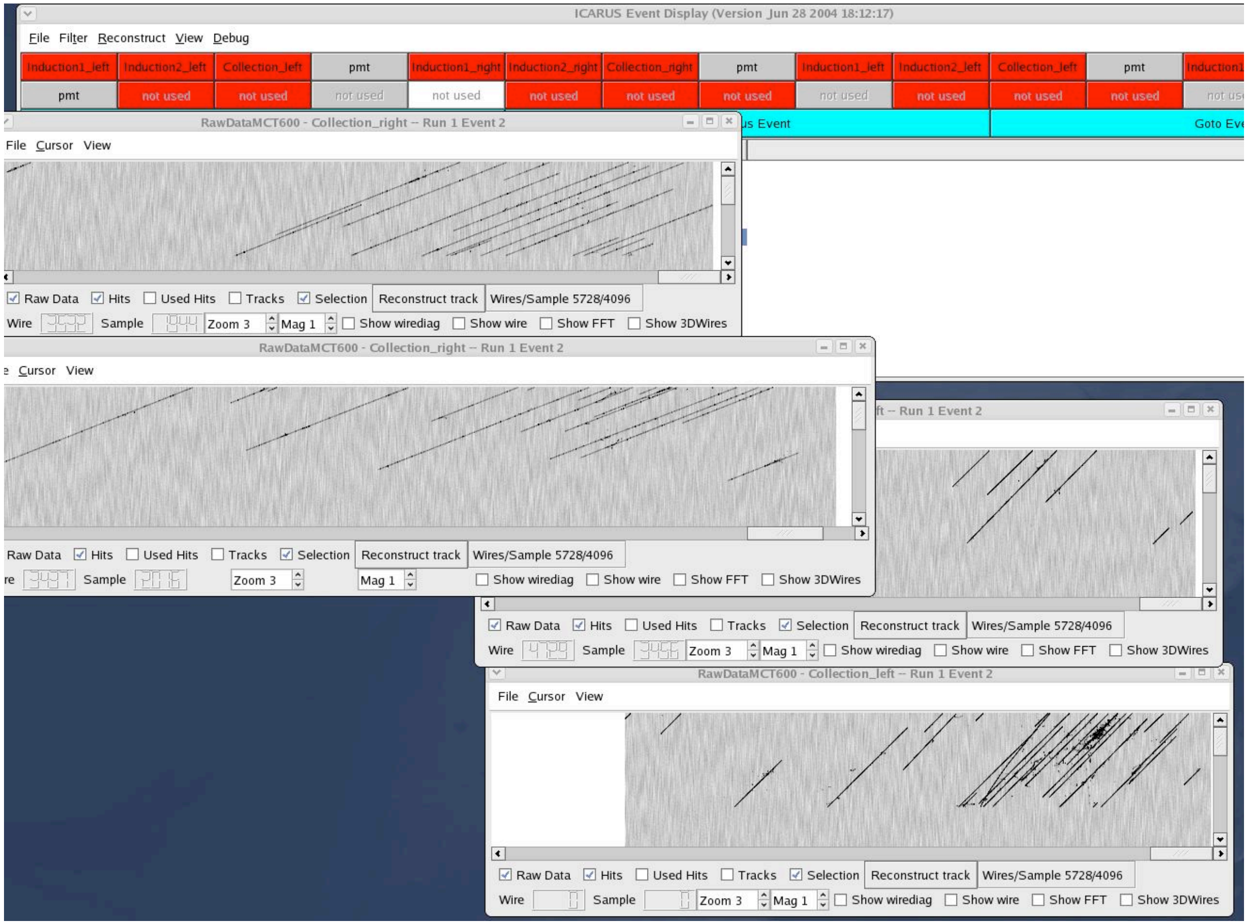
3D earth+atmosphere layered in 100 shells

Input: primary spectra or fixed energies for individual nuclear species

5 mass groups: Z = 1, 2, 7, 13, 26 (spectra from NASA)

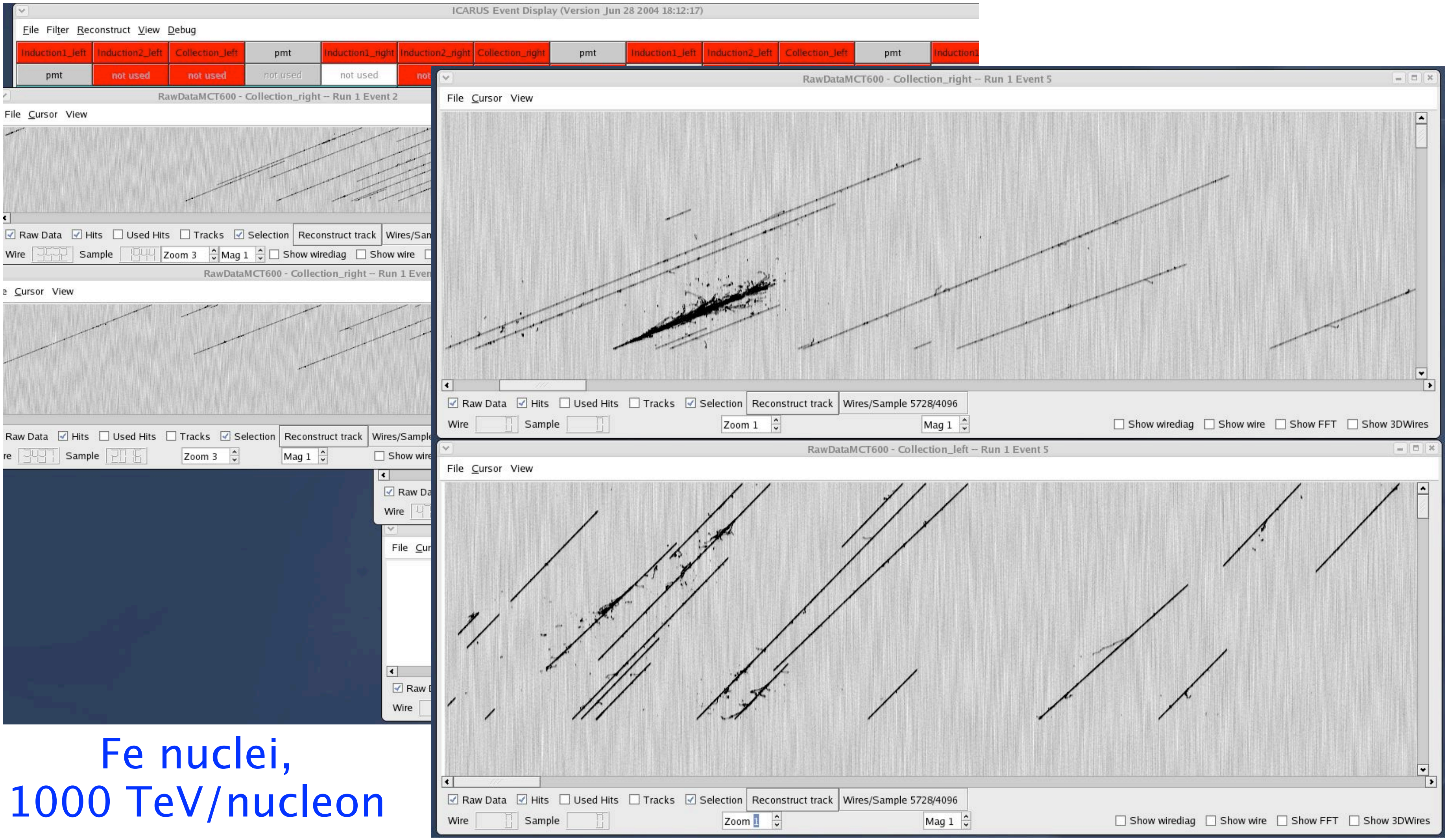
Output: muons (E > 1 TeV) event by event

First results: folding with full simulation in ICARUS



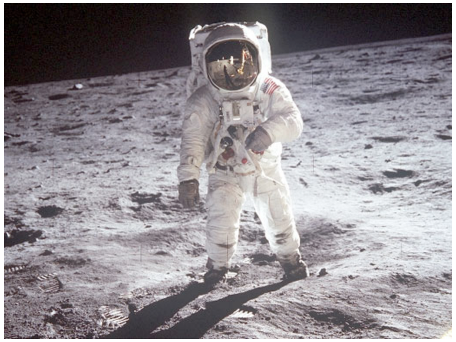
Fe nuclei,
1000 TeV/nucleon

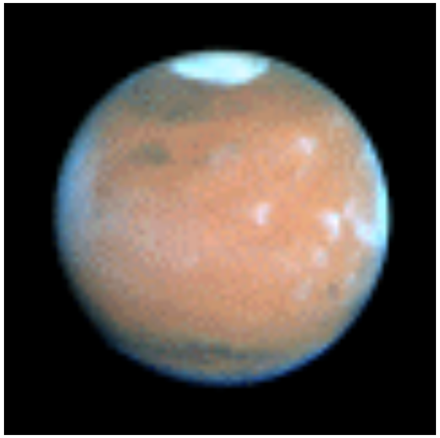
First results: folding with full simulation in ICARUS

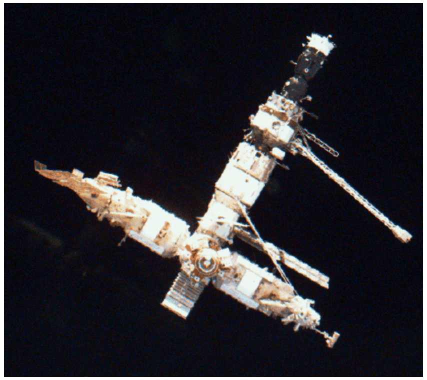


Fe nuclei,
1000 TeV/nucleon

Applications to Space Radiation Protection







- FLUKA ⇒ spatial distribution of absorbed dose delivered by the different components of the radiation field
- "event-by-event" track structure codes ⇒ yields of CL/(Gy cell) induced by different radiation types
- integration ⇒ spatial distribution of CL/cell ("biological" dose)